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R. A. BROCKBANK, Ph.D., B.Sc., A.M.I.E.E.,
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A Paper read before the London Centre of the Institution on 5th February, 1946, and at other Centres during the Session.

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CONTENTS.

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1. INTRODUCTION.

The object of this paper is to review briefly the development of coaxial cable transmission since its inception, to describe the present position reached by this type of transmission and to indicate the general problems involved in the design of wideband systems.

The comparative success of coaxial cable transmission as evinced by the large system development programmes in hand both in this country and abroad is due chiefly to the ease and economy with which large blocks of telephone channels can be provided over long distances by means of a single transmission path. In long distance systems the capital and maintenance costs of the cable or pole line have always predominated over the terminal equipment costs so that any system of multiplexing whereby the line conductors were used more efficiently always resulted in a lower cost per circuit. Thus the development of the thermionic valve and of electric wave filters opened new fields to the telecommunication engineer by permitting the use of supersonic frequencies so that in 1918 the first commercial carrier system was introduced. This system operated on open wire lines and provided three carrier telephone circuits in addition to an audio circuit. Various improvements were afterwards effected, but it was not until 1934—a noteworthy year—that multi-channel telephony appeared in a form which foreshadowed the forthcoming revolution in long distance cable communication technique. The " J " system, which was then introduced in the U.S.A. to provide 12 circuits on a pair of open wire lines, was followed by the " K " system to give 12 channels on each pair of wires in a specially balanced underground cable. The counterpart in this country on underground cables was the Carrier System No. 5 followed in close succession by Nos. 6 and 7, all of which were able to give, initially, 12 channels per pair of conductors. Both the American systems and the Carrier System No. 7 transferred these channels in a single stage of modulation to the range 60-108 kc/s which was accepted as the basic group frequency range for further multichannel carrier system developments at the C.C.I.F. meetings in 1938. The outstanding performance of these systems was achieved by the use of quartz crystal resonators in the filters, a technique which had only been discovered in 1931, and which permitted the channels to be efficiently arranged in this frequency spectrum with a separation of 4 kc/s and yet give improved audio frequency characteristics. Adequate stability of amplification over long distances was made possible by the application of the principle of negative feedback to the repeaters.

The next stage in the development of multi-channel systems was the introduction of coaxial cable transmission which made available such wide frequency bands that hundreds of channels could be simultaneously transmitted. The wide frequency bands available also aroused considerable interest for another reason. Television, to be effective, requires a bandwidth of at least 1 Mc/s and probably considerably more, so that until the inception of the coaxial cable there appeared to be no immediate prospect of relaying television transmission other than by a radio system. Television development was necessarily at a standstill during the war and it is as yet too early in the post-war period to discuss future television transmission prospects.

2. HISTORICAL DEVELOPMENT OF THE COAXIAL SYSTEM.

2.1. General Coaxial Development.

Prior to 1934 cables having a coaxial type construction had only been used for submarine work and as interconnection links between transmitters and their aerial systems, both of which applications needed the transmission of only a narrow band of frequencies. About the time, however, that the " J " and " K " carrier systems were approaching completion as commercial equipments the engineers of the Bell Telephone Laboratories in the U.S.A. were actively engaged in exploring the possibilities of utilizing coaxial cables for what was then considered to be phenomenally wide frequency bands. The first indication that coaxial cables could be employed economically for this purpose was contained in an article(12)* published by them in October, 1934, which contained information regarding an experimental installation and the conclusion was reached that no unforeseen technical difficulties were expected to arise in a commercial system. Apart from the derivation of the characteristics of a coaxial transmission line which had been extended beyond those of earlier mathematicians, the salient points of the system were the wideband negative-feedback repeaters, the system of feeding power over the coaxial tubes, and the triple-modulation process at the terminals with a crystal-controlled carrier generation system.

In retrospect it is difficult to appreciate the surprise and interest with which telecommunication engineers viewed the new system, a system which handled a bandwidth of several megacycles compared with the widest bandwidth of 48 kc/s then in use, and had a loss for a 500-mile circuit of about 4000 db. which had to be precisely balanced by the repeater gains over the whole frequency band.

The British Post Office reacted immediately in favour of this development and decided to experiment with a system between London and Birmingham. The designers (Radio Branch, P.O. Engineering Department) and the manufacturers (Standard Telephones & Cables Ltd.) co-operated so successfully on this project that overall tests were being conducted three years later. These tests were satisfactory and the route was handed over to commercial traffic in April, 1938, with one supergroup of 40 circuits ; the second and third supergroups, each of 40 circuits, were opened in December, 1938, and August, 1939, respectively. This system has since been continuously

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* Numerical references are to the Bibliography at the end of the paper.

available to traffic except for such delays as have been due to war damage to the cable, line-up tests and fault conditions, and it has been carrying a fourth supergroup of 40 circuits routed to Manchester since December, 1940. It is believed that this was the first multi-channel coaxial system in the world to operate commercially and the first to provide traffic on more than one supergroup.

A second coaxial system built to the same design as the London-Birmingham was immediately put in hand between Birmingham and Manchester. This was opened in December, 1940, to operate in tandem with the London-Birmingham section to provide the first supergroup of 40 London-Manchester circuits.

By this time sufficient experience had been gained by the British Post Office in the design and working of these initial experimental coaxial routes to formulate plans for a standardised design of coaxial transmission system. There were so many entirely new factors involved in the first design that it was difficult to assess their relative importance and the degree of success achieved in their application until extensive field operation had been observed. After the original route had been in operation for a year or two it appeared that no major unforeseen difficulties had arisen and that the basic principles of the H.F. repeatered circuit and its supervisories were sound. The C.C.I.F. had meanwhile proposed, and the Post Office had agreed to adopt, a standardised channel separation of 4 kc/s with 12-channel groups based on the frequency range 60-108 kc/s to be formed into 60-circuit super-groups in the basic range 312-552 kc/s. This necessitated alterations to the design of terminal equipment before any further circuits were introduced on the London-Manchester route.

Meanwhile plans were laid for a new design of coaxial system with improved standards of transmission stability, reliability and ease of maintenance. The war, however, interfered with this programme, making it necessary to install a number of hybrid systems to meet temporary commitments requiring, in general, only one or two 60-circuit supergroups.

In America the early commercial development seems to have been slow and the first system installed between New York and Philadelphia appears to have been used for experimental and testing purposes. Publications refer to the Stevens Point-Minneapolis circuit, which was brought into service with 48 circuits in June, 1941, as the first commercial installation. It is probable that the new 12-channel " K " system was given preference over the coaxial system because it was more fully developed for mass production and therefore made less demands on technical maintenance staff.

On the Continent it is known that several coaxial cables were laid, but if they were operated it was probably on a small scale. For example, it is understood that one long coaxial cable in France was used during the war to provide only one earthed telegraph circuit!

2.2. Television Development.

The frequency band of the experimental London-Birmingham system was largely decided on the basis that this route would be used for experimental television transmission. The over-riding need for speech circuits, however, claimed the route before the design was far advanced and thereafter no attention was paid to television requirements. The war then intervened and no further field work on television was conducted by the Post Office.

In the United States, television development continued for a further two years after the outbreak of the European War, when it was then curtailed though not to the same extent as in this country. In 1938 there was described an experimental television circuit over coaxial cables between New York and Philadelphia and in 1940 a more ambitious relay was undertaken over the same route when 441-line television was transmitted very successfully over 98 miles of coaxial cable plus 9 miles of telephone cable.

3. PRESENT STATE OF COAXIAL DEVELOPMENT IN GREAT BRITAIN.

The equipment for a complete coaxial system can best be considered by dividing it into two sections:—

(*a*) the coaxial line equipment, including the cable, and

(*b*) the terminal equipment.

This also represents a division of engineering technique, and as all the coaxial systems installed have been so handled, it is convenient for the description given in this paper to be similarly sub-divided.

3.1. Coaxial Line Equipment.

It is shown later that the evolution of a standardised design of repeater equipment requires the adoption of a standard type of coaxial cable, repeater station spacing, and transmission frequency band. Such standardisation was in hand in 1940, but completion of the final design was of necessity delayed by sudden war-time demands for systems capable of carrying only one or two supergroups. In such instances, it was economical in equipment and labour to install modified equipment sufficient to meet the requirements. As a result, some novel designs had to be produced, and it is of interest to chronicle these non-standard systems before turning to the more important permanent system. A brief reference to the London-Birmingham - Manchester routes is included for continuity.

3.1.1. *Original London-Birmingham and Birmingham-Manchester Systems.*

The basic principles of coaxial transmission and the original experimental equipment used on the London-Birmingham route have already been described in a previous paper.(14) A 4-tube coaxial cable was laid extending eventually from London to Newcastle, but with different constructions of cable in each of the three sections. Fig. 1 (a) (b) and (c) shows the main features of these cables. The replacement of the brass tapes and lead sheath over the individual cores on the Birmingham-Manchester cable by steel tapes was considered to be an improvement, and such tapes have since been incorporated in all multi-tube coaxial cables. Telephone pairs provide supervisory facilities on the repeater equipment and cable.

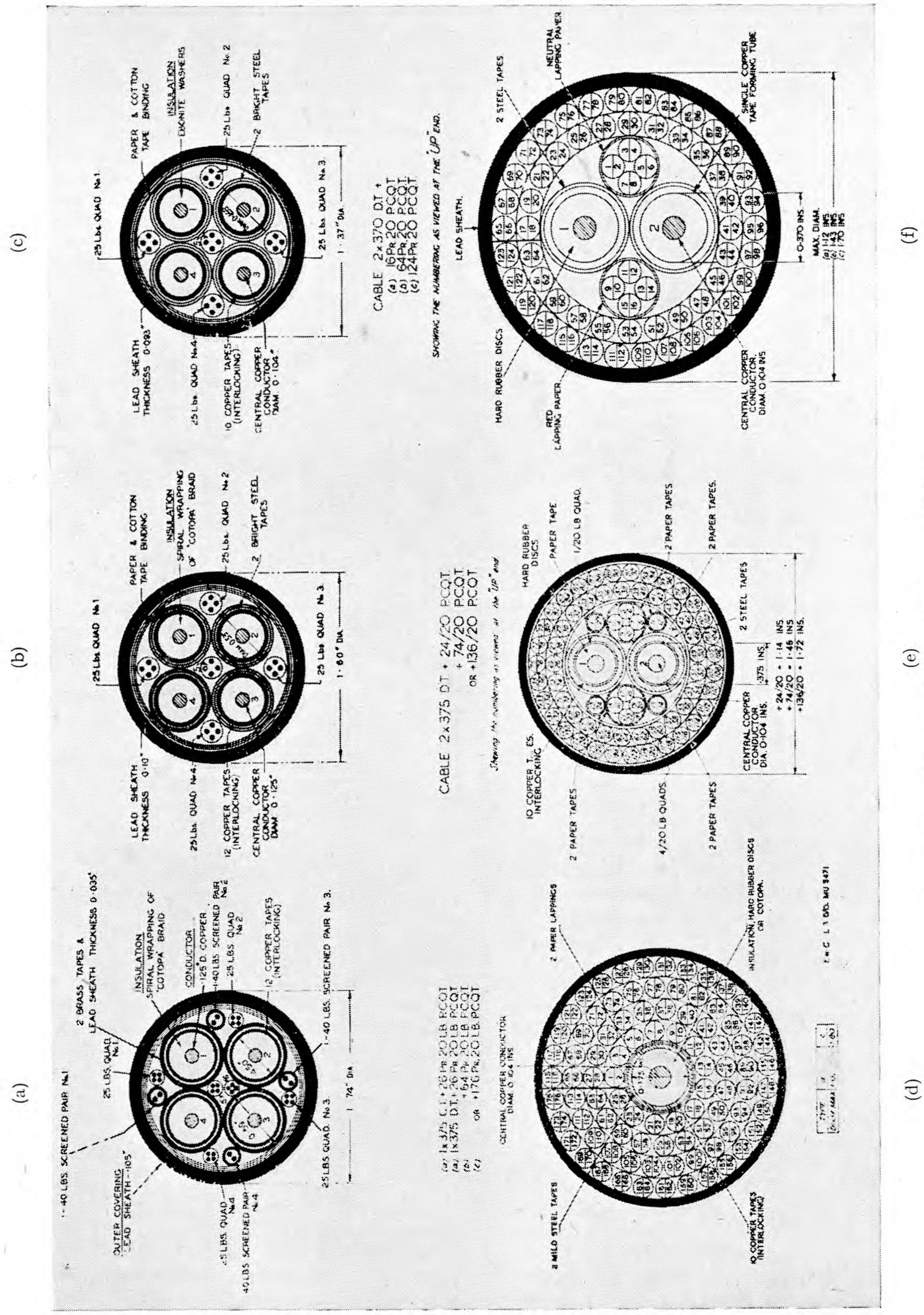


FIG. 1.—TYPES OF BRITISH COAXIAL CABLES. 1935-1945.

The repeater station spacing on the London-Birmingham and Birmingham-Manchester routes did not exceed 8 miles, and this enabled a frequency band of 400-2200 kc/s to be obtained. The 4-valve repeaters contained 6-mile equaliser networks between the first and second valves with feedback over the following three stages. This method of equalisation produces the same resistance noise level on all circuits in the band, but the intermodulation noise increases as the higher supergroups are added. Because intermodulation noise could not be forecast at that time with any considerable degree of accuracy, this method of equalisation was also a safety measure, and ensured that at least a few low-frequency supergroups could be operated with permissible noise values. Standby repeaters with automatic change-over operating from a 2.2 Mc/s transmitted pilot were provided, and these idled on reduced supply volts during non-working conditions with a view to improving valve life. This latter feature has not been perpetuated on later systems.

The necessity for variable equalisation to compensate for changes in cable characteristics due to temperature variations is well known, but no elaborate control mechanisms were tried on these systems, and a network with a characteristic equal to 0.4 miles of coaxial cable was arranged to be switched manually into or out of circuit at each repeater station as required. A voice-frequency supervisory system was provided on one telephone pair for indicating to the control terminal the location of any repeater which changed over. A 2.2 Mc/s transmitted pilot acted as a monitor on the repeaters, and gave a location indication at the control terminal over a voice-frequency supervisory system if the main repeater failed. A 400 kc/s pilot was also transmitted, but this acted only as a locking device for the terminal carrier generation master oscillators. Power failure and supervisory circuit L.F. repeater failures actuated control terminal alarms through a D.C. supervisory circuit, which also included a device for measuring the mean temperature of the cable.

In spite of the fact that these systems have been in service for nearly eight and six years respectively, and have suffered severely during the war, their reliability against breakdown is still surprisingly good, though the overall stability is not satisfactory compared with modern standards.

3.1.2. *Liverpool-Colwyn Bay Coaxial Cable System.*

This system has several points of interest, and it also demonstrates how quickly a simple transmission path for a few supergroups can be provided over coaxial cables. An urgent request for repeater equipment between Liverpool and Colwyn Bay was received in July, 1940, and, in order to meet it, an entirely non-standard repeater equipment was designed and built in the Radio Laboratories and installed before the end of the year.

The first problem arose because the cable consisted of two separate tubes without any supervisory pairs, and no telephone pairs were available in adjacent cables. The normal method of supervision could not, therefore, be used, and a new scheme had to be devised which employed a D.C. earth-return circuit on the centre conductor of each tube. These two circuits gave an indication at the control terminal (Liverpool) when—

(*a*) any main repeater changed to its standby, and
(*b*) a complete failure of either H.F. path occurred at any station.

Either of these fault conditions caused a resistive earth of carefully selected value to be placed on the D.C. circuit, thereby operating the appropriate sensitive alarm relay at Liverpool. Measurement of the loop resistance of this D.C. path enabled the maintenance officer to identify the faulty station, and the resistance values were so chosen that accurate location of simultaneous faults at two or three stations could be made by reference to a calibration table. This simple arrangement was possible because there were only four intermediate repeater stations on the 53 miles route.

The choice of a repeater was also difficult ; the London-Birmingham type was not suitable, and the final design of the present standard 3-valve repeater was not sufficiently advanced. The repeater finally employed was a 5-valve arrangement, the last two in push-pull, on which some development work had previously been conducted in the laboratory.

Because of lack of certain components, the transmitted pilot supervisory system could not be employed, and a new scheme was, therefore, developed whereby a single valve oscillator was connected permanently to the input of each main repeater, and a suitable selective detector valve connected to the output. The working band of the system was 300-1300 kc/s, and the single valve oscillator and detector were each tuned to operate at 2600 kc/s. In the event of the main repeater failing, the detector circuit operated and connected the standby into circuit. There are three points of interest in connection with this supervisory system:—

(*a*) The attenuation of the cable at this higher frequency was sufficient to ensure that no interaction occurred between pilots at successive stations.
(*b*) No second-order intermodulation products generated by the 2600 kc/s could lie within the working band, and
(*c*) The feedback on the repeater at 2600 kc/s was comparatively low, so that changes in the repeater gain were more pronounced than in the working band.

This system has now been in service for four years, and has met the design requirements and performed satisfactorily.

3.1.3. *Mark IV Repeater Equipment.*

The ease with which a wide transmission band can be provided by coaxial cable technique suggested that the use of portable repeater stations connected by a flexible cable might offer a quick means of providing a large number of temporary circuits. This might have obvious applications in war-time for interruption circuits or temporary field communication, or the units might be used to replace damaged fixed stations operating on a standard coaxial trunk route. The general requirements for these units were compactness, low power consumption and water tightness. This unit became realisable in 1940, when a new high-efficiency battery pentode, the VT 182, was produced experimentally and the construction of an experimental portable repeater unit was then put in hand. The model which was developed is shown in Fig. 2 and it was designed to operate with a frequency band 60-552 kc/s (120 circuits). Main and standby 2-stage feedback repeaters having a flat gain of 45 db. were included with automatic change-over operated by a 1.2 Mc/s local oscillator and selector as described for the Liverpool-Colwyn Bay system. A similar type of D.C. supervisory on the tubes was also provided.

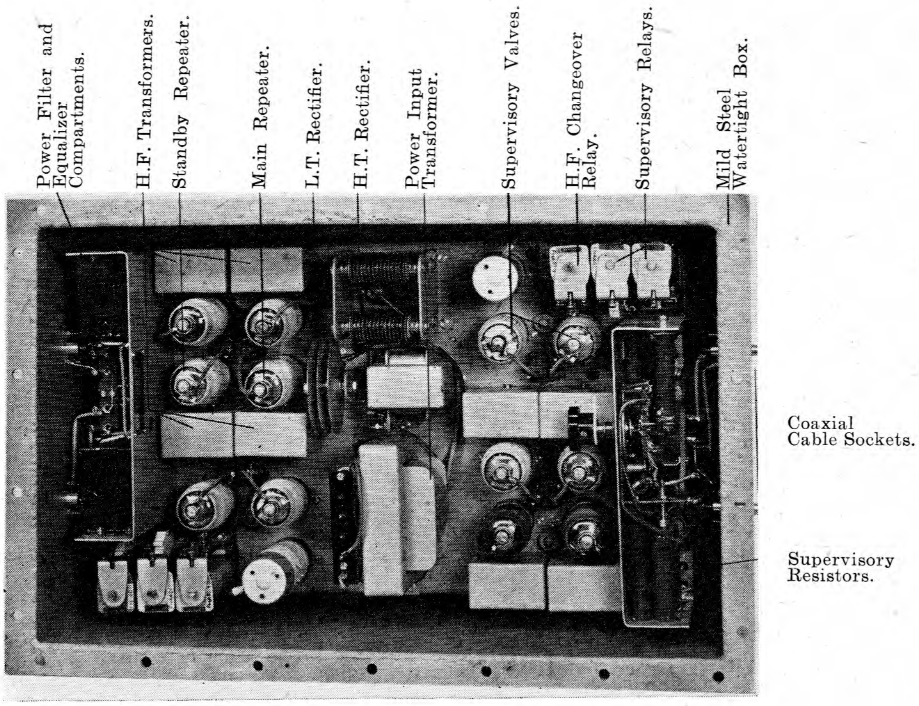


FIG. 2.—MARK IV. REPEATER UNIT. COVER REMOVED.

The filament of each valve required 150 mA at 2 volts D.C., and the total power consumption of the unit with its 14 valves was 18 watts, permitting a route length of about 170 miles of $\frac{3}{8}''$ diameter tubes to be fed with power only from the terminals.

The Mark IV repeater unit has not yet been used with a flexible cable, but it provided urgent circuits between Inverness and Wick for 18 months, and, more recently, it has been working satisfactorily on the London-Salisbury route since April, 1944, awaiting the completion of permanent equipment. The valve life has unfortunately proved to be less than was expected and a complete replacement of all valves is necessary every three months.

3.1.4. *Unit Bay 1B Repeater System.*

The Unit Bay 1B repeater system represents the outcome of earlier design, test and field experience, and it is the basic standard system now being used for extending the trunk network of this country. A more recent version of the equipment is known as "Coaxial Equipment, Line No. 1," but it differs from the standard Unit Bay 1B equipment in only a few details concerned chiefly with the supervisory circuits.

The Unit Bay 1B repeater system is now being described by the authors elsewhere(15) and only a summarised version will be included here. The system provides a two-way transmission path over separate coaxial tubes for a bandwidth of 60-2852 kc/s (660 circuits with 4 kc/s spacing) over a maximum of 24 repeater sections each of which must not exceed six miles. It is designed to operate with $\frac{3}{8}''$ internal diameter tubes laid up in a 2-tube coaxial cable of 75 ohms impedance containing at least eight 20 lb. unloaded telephone pairs, as shown in Fig. **1**. The system is operated from the 50 c/s power supply mains at about every fifth station, so that two dependent intermediate stations are fed on each side from a central power-feeding intermediate station. The Unit Bay 1B equipment installed at a repeater station is shown in Fig. **3**. A single type of valve, the pentode VT 150, is used at all repeater stations, and the 3-valve feedback repeaters, each provided with automatic change-over to standby, are monitored continuously by a 300 kc/s transmitted pilot. One sectionalised 6-mile equaliser with a relay-controlled temperature equaliser network precedes each repeater, so that any cable length between 2.8 and 6.0 miles can be equalised to ± 0.1 mile by suitable tag connections during installation. All supervisory indications are signalled to the control terminal on the telephone pairs, and this terminal therefore becomes responsible for originating all route maintenance and control. An independent repeater change-over lamp signal is provided at this terminal for each station on the route, and power and L.F. supervisory repeater failures can also be located.

The control terminal has facilities for changing over any main to standby repeater, and can also effect remote switching of all temperature equalisers in order to maintain a substantially constant gain at all frequencies in the band. An automatic gain control system operating at each receive terminal from the incoming 300 kc/s transmitted pilot corrects residual variations in gain at this frequency, and in conjunction with a 2852 kc/s pilot gives a meter indication of the overall slope of the system. These two pilots are also used to drive a fully automatic temperature equaliser control unit, which can be switched into circuit if it is desired to make the operation entirely automatic.

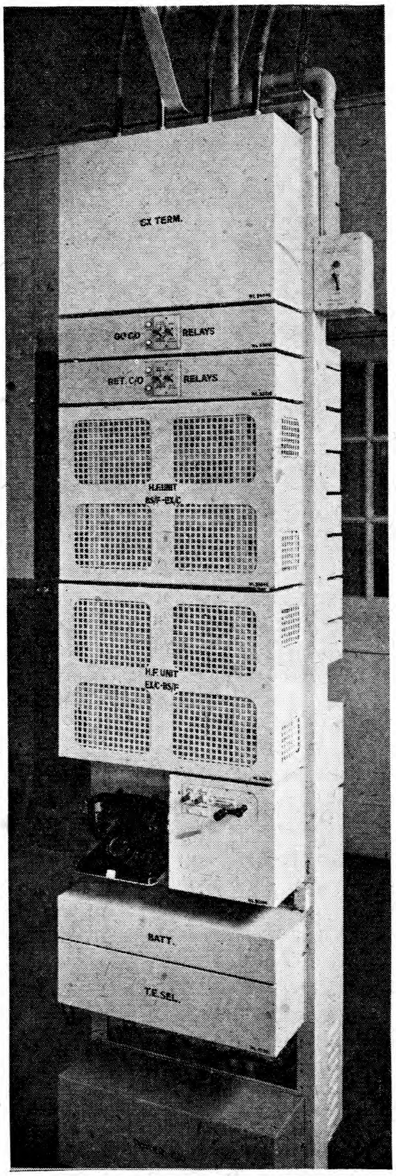


FIG. 3.—UNIT BAY 1B AT AN INTERMEDIATE STATION.

Brief transmission characteristics of the system are:—

Working Signal Band	60-2788 kc/s, *i.e.*, 11 supergroups (660 circuits).
Pilots...	300 and 2852 kc/s at a level of + 3 db. rel. to 1 mW at each repeater output.
Channel Level ...	− 13 db. at repeater output rel. to 2-wire sending level.
Gain Stability ...	± 0.2 db. at 300 kc/s and ± 2.0 db. at 2788 kc/s.

Maintenance tests at intermediate stations are carried out only at yearly intervals when all H.F. repeater valves are replaced and all supervisory valves checked in the valve tester provided on each bay. For installation, fault repairs and maintenance, a portable transmission measuring set has been designed

FIG. 4.—PORTABLE H.F. TRANSMISSION MEASURING SET.

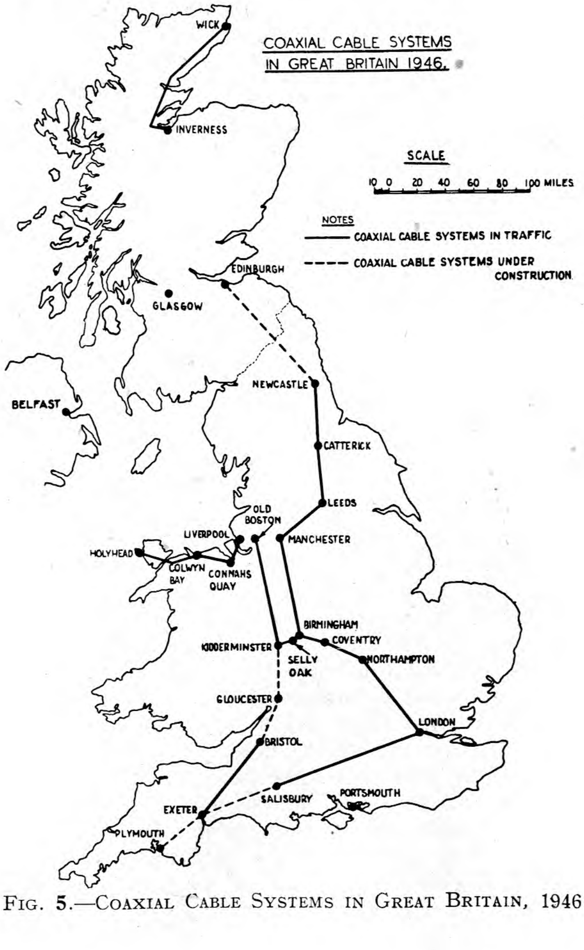


FIG. 5.—COAXIAL CABLE SYSTEMS IN GREAT BRITAIN, 1946.

which will carry out all the H.F. tests normally required on the repeater system. This instrument is known as Tester WL 56265, and is shown in Fig. **4**.

3.1.5. *Coaxial Installations in Great Britain.*

Table 1 lists the coaxial cable systems on which work by the Department was completed or in progress in January, 1946, and Fig. **5** shows their geographical disposition.

TABLE I.

DETAILS OF COAXIAL CABLE REPEATER INSTALLATIONS IN GT. BRITAIN, JANUARY 1946.

Route	Type of Cable in Fig. 1	Nominal Maximum Repeater Station Spacing	Type of Equipment	Frequency Band Available kc/s	Date in Service
		Miles			
London-Birmingham Tubes 1 & 2	(a)	8	A	400-2200	April 1938
Birmingham-Manchester Tubes 1 & 2	(b)	8	A	400-2200	Dec. 1940
Liverpool-Colwyn Bay	(d) mod.	12	B	300-1300	Jan. 1942
Inverness-Wick	(d)	25	E	60-408	June 1943
Colwyn Bay-Holyhead	(e)	12	E	300-1364	Feb. 1944
Bristol-Exeter	(e)	12	E	60-850	April 1944
London-Salisbury	(e)	6	C	60-552	April 1944
Selly Oak-Kidderminster-Old Boston	(e) & (d)	6	E	300-1364	May 1944
Manchester-Newcastle Tubes 1 & 2	(c)	8	E	300-2356	In Progress
London-Birmingham Tubes 3 & 4	(a)	8	G*	60-3200	,,
Birmingham-Manchester Tubes 3 & 4	(b)	8	E	60-2356	,,
Manchester-Leeds } Tubes 3 & 4			H	108-350	1939
Leeds-Newcastle } Tubes 3 & 4	(c)	8	E**	60-2356	In Progress
Bristol-Kidderminster	(e)	6	F	60-2852	,,
Salisbury-Exeter	(e)	6	F	60-2852	,,
Newcastle-Edinburgh	(f)	6	F	60-2852	,,
Exeter-Plymouth	(e)	6	F	60-2852	,,
Connahs Quay-Old Boston	(e)	not	decided		
London-Elstree (By-pass)	(e)	8	E	60-2200	,,
London Interconnection Ties	(e)	—	E	60-2852	,,
Training School, Cambridge	—	—	D	60-2852	1945

* Standby repeaters 60-2108 kc/s.

** Replacing H.

A.	First experimental equipment.
B.	Special equipment for this route.
C.	Portable Mark IV Equipment.
D.	Standard Unit Bay 1B.
E.	Modified Unit Bay 1B.
F.	Coaxial Equipment, Line No. 1.
G.	Experimental Television Amplifier Equipment.
H.	Early STC Equipment.

3.2. Coaxial Terminal Equipment.

3.2.1. *Channel Assembly by Multiple Modulation.*

The general principles by which a number of telephone channels can be assembled side by side as amplitude-modulated carrier sidebands in a high-frequency spectrum are now well known. The method universally adopted is to assemble the individual channels by processes of successive modulation, each step of which handles a wider band at a higher frequency until the final single H.F. band is achieved.

Features of this successive modulation process to assemble a large number of channels into a wide frequency band are:—

(*a*) Single-sideband transmission with suppressed carriers can be employed, thereby making the most economical use of the frequency band and obtaining lower signal loading on the repeatered line for a given number of channels.

(*b*) Simplicity in design and construction is obtained because most of the terminal equipment consists of repetitions of a few basic designs.

(*c*) Quartz crystal filters can be used following the first stage of modulation as they give the most efficient means of assembling the channel sidebands without mutual interference. In the second and third stages of frequency translation coil-condenser filters are then adequate.

(*d*) The number of carrier frequencies which must be generated is reduced in a 600-channel system to less than 30. These are all derived from a single quartz oscillator of high stability to which all carrier frequencies are therefore locked.

(*e*) Flexibility in routing of circuits is greatly increased as they can be handled in supergroups of 60 or groups of 12, extracted between the stages of frequency translation.

The early American field experiments at Morristown used two stages of modulation for the frequency band 60-1020 kc/s and three stages for the New York-Philadelphia system. The British Post Office has so far only used triple modulation, the three stages being known as channel, group and supergroup modulation respectively.

3.2.2. *London-Birmingham Experimental* 8/5/8 *System.*

These points were duly considered in 1935 when the terminal equipment for the London-Birmingham route was planned. Not least among the novel problems encountered was the production of a suitable train of carrier frequencies, and it was decided to employ a decimal system of frequency relations between successive modulation stages. The arrangement adopted was known as the 8/5/8 system ; 8 channels (5 kc/s spacing) formed one group (60-100 kc/s), 5 groups formed the basic supergroup (300-500 kc/s) and 8 supergroups filled the transmission spectrum 500-2100 kc/s. Provision for reducing the channel spacing to 4 kc/s, *i.e.*, a 10/5/8 system, was made when the equipment was built, but it is now unlikely that the conversion from 5 kc/s to 4 kc/s spacing will ever be carried out on the original equipment.

The channel modulation stage used copper-oxide ring-modulators followed by lattice crystal filters with the outputs connected in parallel, the upper sidebands and carriers being suppressed. Channel amplifiers were used at the receive end only. The group and supergroup stages each employed balanced valve modulators followed by coil-condenser filters combined alternately on opposite sides of hybrid transformers to prevent interference between adjacent supergroups. The upper sidebands and the carriers were again suppressed. The equipment required for each supergroup covered eleven 10 ft. 6 in. bay sides and all the power was derived from the 130 and 24-volt station batteries. The carrier frequencies were derived from multi-vibrators locked to a 400 kc/s master crystal oscillator and this carrier generating equipment installed in duplicate required eight 10 ft. 6 in. bay sides.

Four 40-circuit supergroups built to the 8/5/8 system were installed at London, between 1938 and 1941 ; three terminated at Birmingham and the fourth at Manchester, and all have given a satisfactory performance to the standard envisaged in the experimental design.

3.2.3. *C.C.I.F. Recommendation for Frequencies.*

In 1938 the problem of the international standardisation of multi-channel carrier system designs came before the C.C.I.F. as it was apparent that for economical and flexible working the various 12-channel and coaxial systems should be capable of ready interconnection. The Committee recommended the American arrangement which used 4 kc/s spacing with 12 channels in the basic group range 60-108 kc/s and five groups in the basic supergroup range 312-552 kc/s. Spacings of 12 kc/s were then allowed between the first three supergroups and 8 kc/s between all higher frequency supergroups as shown in Fig. **6**.

Subsequent American practice has reduced the spacing between Supergroups 1 and 2 to 4 kc/s, so that Supergroup 1 falls in the band 68 kc/s to 308 kc/s. The carrier frequency for Supergroup 1 is then 620 kc/s. This is readily obtained as the 5th harmonic of 124 kc/s, and it is then a member of the family of supergroup carrier frequencies.

Supergroup 2 coincides with the frequency of the basic supergroup band and hence it passes from the group combining point to the supergroup combining transformer without a third stage of modulation (Fig. **6**). Supergroup 2 therefore appears to be "inverted" with respect to the other supergroups.

3.2.4. *London-Birmingham* 12/5/8 *System.*

The Post Office decided to add two more supergroups to the London-Birmingham route in conformity with these C.C.I.F. recommendations, but to retain the original 8/5/8 supergroups unaltered. Contracts for these two additional supergroups were placed in 1939 and 1941 respectively, but the manufacture has been so much delayed by war conditions that the equipment was obsolete before installation, which is now in progress, commenced. The supergroups will carry traffic between London-Newcastle and London-Birmingham respectively.

3.2.5. *Coaxial Carrier System No.* 7 *Terminal Equipment.*

The 12-channel Carrier System No. 7 employing C.C.I.F. frequencies is similar to the American K System, and since it was in full production early in the war it has formed the basis for most of the coaxial terminal equipments which have been installed on routes other than London-Newcastle Tubes 1 and 2.

The channel equipment, which is now well known in 12-channel systems in this country, gives six circuits on each 10 ft. 6 in. bay side. The group stages employ double-balanced copper-oxide modulators with sealed coil-and-condenser band-pass filters, and incorporate two-stage amplifiers in the receive direction. The supergroups also use coil and condenser band-pass filters and double-balanced copper-oxide modulators except for the basic supergroup No. 2 which passes through unmodulated. Supergroups Nos. 1 and 3 are treated exceptionally because they are adjacent to the basic supergroup band and therefore need to be equipped with a low-pass and a high-pass filter respectively, in addition to a single common low-pass filter to provide discrimination above 804 kc/s. These filters are all of the coil-condenser type.

The carriers are all derived from the 4 kc/s motor-controlled master oscillator which forms part of the

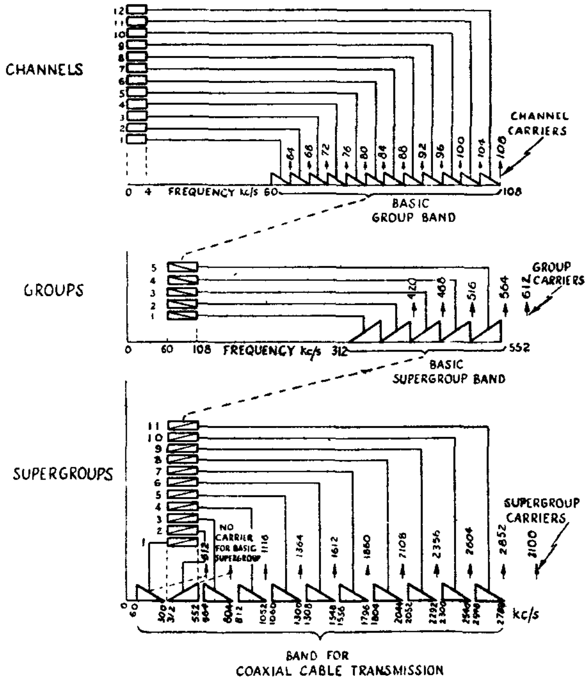


FIG. 6.—FREQUENCY ALLOCATION FOR COAXIAL TERMINAL EQUIPMENT PROPOSED BY C.C.I.F.

Carrier No. 7 Channel System, by harmonic generators of the saturated-coil type. Group carriers are derived as odd harmonics of 12 kc/s from a harmonic generator driven from the 3rd harmonic (12 kc/s) of the master oscillator. The supergroup carriers for Supergroup 3 upwards are odd harmonics of a 124 kc/s train produced by a harmonic generator driven by the 31st harmonic (124 kc/s) of the master oscillator. Supergroup No. 1 uses the 612 kc/s carrier generated in the group carrier train.

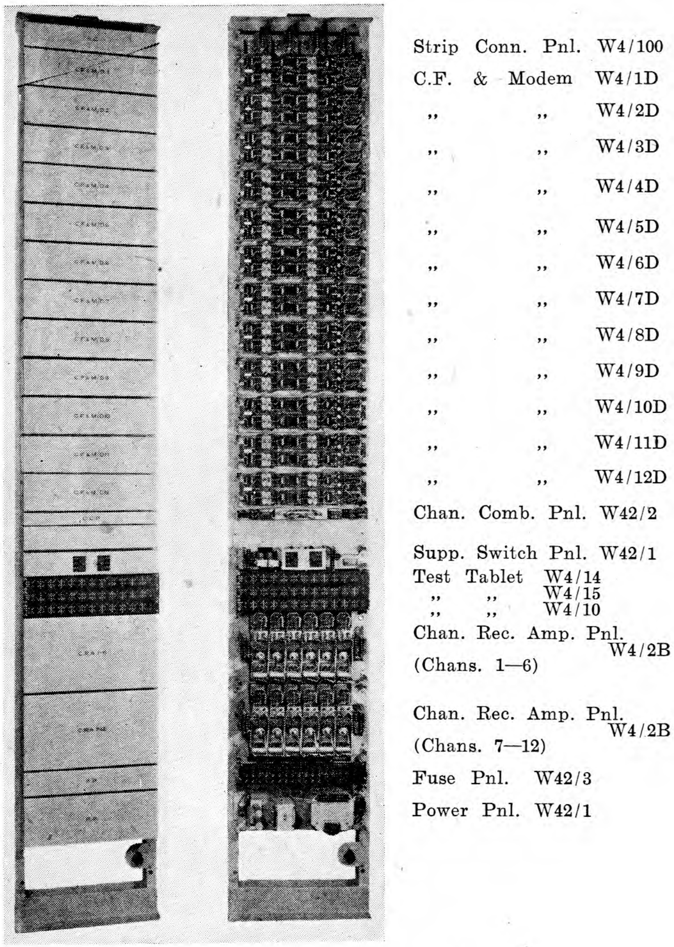
3.2.6. *Coaxial Carrier System No.* 8 *Terminal Equipment.*

The Coaxial Carrier Terminal Equipment No. 8 is a Post Office (Radio Branch) design and it incorporates the result of the experience gained on the London-Birmingham-Manchester-Newcastle coaxial terminals. This equipment was intended originally for operation in conjunction with the Unit Bay 1B Coaxial Repeater System and the design of the first frequency stage—the channel equipment—was completed in 1942. Some 800 circuit ends of this type were built for use in terminating multi-channel ultra-short wave radio links and many of these have seen service in various war theatres. The development of the group and supergroup stages was interrupted for two years, but four supergroup ends of this new equipment are now being installed for trial on the London-Manchester-Newcastle route, Tubes 1 and 2, and new Carrier Generation Equipment No. 8 is being designed to work with it. All this terminal equipment uses C.C.I.F. frequency allocations, Fig. **6**, and is operated directly from 50 c/s supply mains. It occupies approximately half the space of the existing coaxial terminals as the complete equipment for 600 circuit ends is accommodated on thirty-one 10 ft. 6 in. double-sided bays, giving an average of approximately 13 ins. of bay side per telephone circuit. The design anticipates that future trunk demands will require "Through - Group" or "Through - Supergroup" working with as many as four coaxial systems in tandem and therefore the overall telephone channel pass-band performance, the degree of carrier suppression, and, in particular, the level stability margins, are calculated on this basis. An overall system of continuously variable supergroup automatic gain control forms a novel part of the Coaxial Terminal System No. 8 and it is designed to give the audio channels a long-term stability of ± 1.0 db. over 500 miles of coaxial trunk network irrespective of small repeatered line variations.

The frequency translating equipment has been designed in four distinct sections, each contained on separate bays, known respectively as the Channel Equipment No. 8, the Group Equipment No. 8, the Supergroup Equipment No. 8, and the Supergroup Automatic Gain Control. Each bay is self-contained in that it has its own power supply panel with one junction point to the 50 c/s 240 volt station A.C. Mains Supply.

3.2.6.1. *Channel Equipment No.* 8.

Each side of one 10 ft. 6 in. channel bay (Fig. **7**) carries the complete translating equipment for 12 circuit ends. This is achieved by mounting both the transmit and receive equipment for one 4-wire circuit, comprising two lattice crystal filters, copper-oxide double-balanced modulator and demodulator, transformers and attenuators, on a single panel. Channel receive amplifiers, mounted six on a panel, amplify the circuits on the receive side.



Front View Front View (Covers removed)

FIG. 7.—CHANNEL EQUIPMENT NO. 8.

The response limits which were agreed within the Department for back-to-back tests on a channel bay, compared with the corresponding limits for audio-to-audio response on a trunk circuit proposed by the C.C.I.F. in 1938 are shown in Fig. **22**. (See Section 6.2.1.)

3.2.6.2. *Group Equipment No.* 8.

One double-sided 10 ft. 6 in. bay accommodates 6 sets of 5 group modem panels, *i.e.*, sufficient for five complete supergroups plus a set of spares. The group modems use coil-and-condenser filters and double-balanced copper-oxide modulators. Metal rectifier technique does not yet seem to have overcome the slight ageing instability in copper-oxide rectifiers and as this effect becomes increasingly troublesome at higher frequencies, the carrier suppression is not obtained from the ring modulators alone, but is backed-up by networks in the group band-pass filters.

This ensures adequate margin against the normal ageing deterioration in copper-oxide modulator balance. A two-stage group-receive feedback amplifier follows each demodulator. Fig. **8** shows the modem panel which carries the complete send and receive equipment for one group. Unit construction is employed, with fully coaxial inter-connection throughout, and level test points are fitted for convenient transmission testing. The spare set of modem panels is wired to a jack field panel, so that if a spare is required in service it can be connected by coaxial test leads in a few seconds.

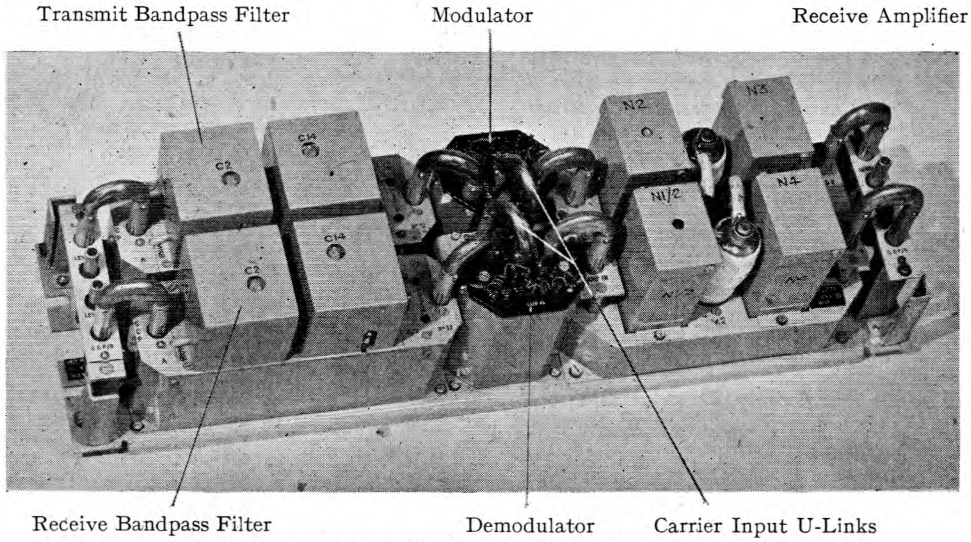


FIG. 8.—COAXIAL CARRIER EQUIPMENT NO. 8. GROUP MODEM PANEL.

3.2.6.3. *Supergroup Equipment No.* 8.

Balanced pentode valve modulators are preferred for use at the higher frequencies needed at the supergroup stages because:—

(*a*) Their stability of balance over long periods without adjustment has been found to be superior to that of metal rectifiers at these frequencies.

(*b*) The voltage gain inherent in this type of modulator permits a reduction in the number of supergroup amplifiers.

In the supergroup translating stage of the Coaxial Equipment No. 8 a high degree of transmission gain stability is not essential, because this equipment is included in the path of the supergroup automatic gain control. It is desirable that supergroup modulator balance should remain good however. This is particularly the case in supergroups Nos. 1 and 3 where the suppression of the basic supergroup band, which coincides with supergroup No. 2 is most important. On this account, high performance low-pass and high-pass crystal filters are included in supergroups Nos. 1 and 3 respectively to give adequate suppression to straight through signals, which would otherwise give crosstalk into the basic supergroup band, *i.e.*, into supergroup No. 2.

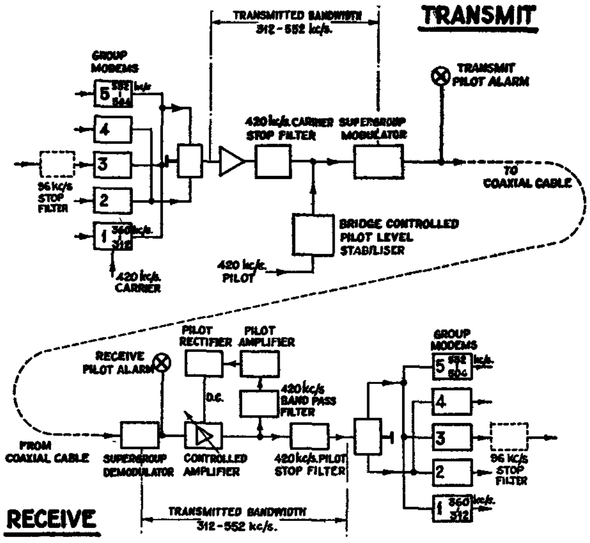
Hermetically sealed coil-condenser band-pass filters are used after each supergroup frequency translation to select the wanted sideband.

An alternative form of modulator is now being examined using crystal valves which offer promising advantages for this and other applications.

3.2.6.4. *Supergroup Automatic Gain Control.*

This is a recent innovation in coaxial trunk working, designed to give automatic stabilisation of the transmission gain over each complete supergroup path to within the limits ± 0.25 db. A stability within ± 1.0 db. can then be realised between channel 4-wire terminations. The controlled supergroup path may be several hundred miles in length, as it commences at the input to each send supergroup modulator (*i.e.*, in the basic supergroup frequency range 312-552 kc/s), extends through the supergroup modulating equipment, over the repeatered coaxial cable and eventually through the receive supergroup demodulator at the distant terminal. Here the automatic gain-controlled amplifier operates at the supergroup output in the frequency range 312-552 kc/s. This control could be extended continuously over any number of coaxial systems connected in tandem, provided that " through-supergroup " or " through-group " working is used. In the latter case it is necessary for groups to be reassembled in the same order into the supergroups of successive coaxial systems. In the former, complete supergroups could be rearranged at the junctions without disturbing the overall level control on each supergroup path. If separate groups are to be extracted from a supergroup it may prove desirable to make the point of extraction a point of supergroup automatic gain control.

The controlling monitor is a 420 kc/s pilot which is injected at a stabilised level into each send supergroup as it passes through the basic frequency range 312-552 kc/s at the beginning of the section to be controlled. The pilot falls between channels 9 and 10 in Group 3 without causing disturbance in either. It is then modulated, in company with all the other signals in the supergroup, into its designated position in the coaxial cable transmission band and is transmitted over the repeatered path to the remote terminal. Here, all the supergroups are reduced to the basic supergroup frequency band and the deviations from normal of the received 420 kc/s pilot levels will represent changes in gain of the respective supergroup transmission paths. Thus by extracting the 420 kc/s pilot from the output of each supergroup demodulator with a narrow band crystal filter connected across the transmission path, the filter output level can be used to control the gain of a variable amplifier following the supergroup demodulator output. The block circuit is shown in Fig. **9** for a single supergroup. The supergroup A.G.C. unit of the Coaxial Equipment No. 8 works between points of equal level and 75 ohms impedance, so that it can be inserted in the wiring between group and supergroup translation stages. The unit is equally able to work in conjunction with Coaxial Equipment No. 7 or the original experimental 8/5/8 equipment used on the London-Manchester route. There are therefore advantages in mounting a number of units on a distribution frame and allocating them in much the same way as through supergroup filters.



NOTE:- 96 kc/s. PILOT STOP FILTER IS ALTERNATIVE TO THE 420 kc/s. STOP FILTER.

FIG. 9.—COAXIAL CARRIER EQUIPMENT NO. 8. BLOCK DIAGRAM OF SUPERGROUP AUTOMATIC LEVEL CONTROL.

Narrow band pilot-blocking filters at both transmit and receive terminals prevent any pilot leakage into the rest of the equipment, or any falsification of pilot level by interference from carrier leaks which would otherwise fall on the same frequency.

It will be noticed that the control gear design can be identical for each supergroup as it operates within the basic supergroup frequency band (312-552 kc/s) of each supergroup. Also, each supergroup is controlled independently of all the others. All the total small gain errors which accumulate in the repeatered line, together with those in any intermediate terminal link points, such as " through-supergroup " connections, and in the send and receive supergroup modulator and demodulator translating stages will be reduced to within ± 0.25 db. at the pilot frequency (420 kc/s) in each supergroup. The only portion of a coaxial circuit which will not be controlled in gain will then be the channel and group translation stages at each end.

A control frequency of 420 kc/s was chosen for the first field installations because:—

(*a*) It is approximately mid-way between the limiting frequencies 312 and 552 kc/s of the band, thus giving both the extreme channels the smallest possible level variation.

(*b*) 420 kc/s is a carrier frequency readily available in the existing carrier generation equipment.

(*c*) 420 kc/s is suitable for application both to the original London-Manchester 8/5/8 (5 kc/s channel spacing) system and the Coaxial System No. 7.

The pilot level at present being used is the same as the relative channel test level. Results have shown that the 420 kc/s selection filter is adequate to permit a level 10 db. below this, however, should it prove desirable.

Full scale trials are in progress on the London-Birmingham Supergroup 6 on Tubes 1 and 2 of the coaxial cable and on the London-Manchester Supergroup 7. On both of these the control equipment can give automatic correction of level variations up to ± 10 db. On routes equipped entirely with Unit Bay 1B repeater stations, correction limits of ± 3 db. should be adequate, and a simpler design of the Supergroup A.G.C. equipment can then be employed.

A simple, yet valuable, supergroup transmission alarm scheme is associated with each 420 kc/s pilot whereby failure of any supergroup translating stage is automatically located within the terminal concerned.

Fig. **10** shows level recordings made during the first field tests of an experimental supergroup A.G.C. unit working between London and Newcastle on Supergroup 6 before this was opened for traffic. A free oscillator had to be used as a pilot source in these early tests and the unrelated drift in the lower curve represents slight pilot changes due to frequency wandering over the pass-band of the 420 kc/s pilot selecting filter.

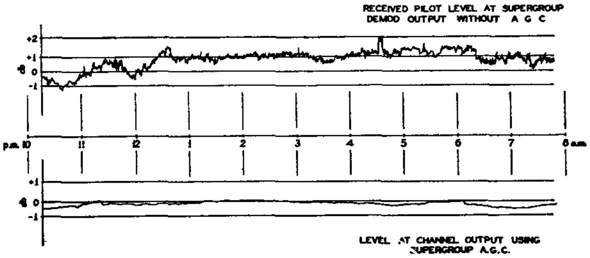


FIG. **10**.—LEVEL RECORDINGS. SUPERGROUP A.G.C. EXPERIMENT. NEWCASTLE-LONDON SUPERGROUP 6.

3.2.6.5. *Carrier Generating Equipment No.* 8.

The carrier generating equipment intended for use with the Carrier Translating Equipment No. 8 is not yet completed, but work is proceeding on a design which it is anticipated will be as follows:—

Three ranges of carrier frequencies are required.

(*a*) The twelve channel carriers, 64, 68, 72, . . 108 kc/s which are the 16th to 27th harmonics of 4 kc/s are selected by narrow band crystal filters from a pulse generator locked to a 4 kc/s source.

(*b*) The five group carriers, 420, 468, 516, 564 and 612 kc/s which are the 35th, 39th, 43rd, 47th and 51st harmonics of 12 kc/s which is itself selected as the 3rd harmonic of the 4 kc/s.

(*c*) The supergroup carriers, 1116, 1364, 1612 kc/s . . . 2356 kc/s which are the 9th, 11th, 13th, 15th, 17th and 19th harmonics of 124 kc/s which is itself the 31st harmonic of 4 kc/s.

The first supergroup carrier, 612 kc/s, can be derived from the group carrier train. The second supergroup requires no carrier as it passes through unmodulated.

Ultimately it will be possible to use a 4 kc/s quartz crystal, probably vibrating in a flexural mode, as a primary source of frequency. Until this low crystal frequency technique is more developed, however, a 60 kc/s crystal source will be used.

In each of the trains the harmonics are selected by filters from the outputs of trigger circuits which generate pulses at the frequency of the input signal. The pulse outputs are rich in harmonics of their repetition rate and so provide an excellent source for carrier production.

The crystal oscillator source and channel carrier equipment are on one self-contained, A.C. driven, bay and the group and supergroup equipment are on a second bay.

4. PRESENT POSITION OF COAXIAL CABLE DEVELOPMENTS ABROAD.

In view of the lack of reliable and complete data on conditions abroad, it is only possible to offer a few general remarks. On the Continent, coaxial systems were being introduced at the beginning of the war but any equipments that were installed were probably only of a temporary or immature nature, and are unlikely to be of great interest to post-war developments.

In America the technique of coaxial transmission has been consolidating steadily during the war as the result of experience gained on two systems which have been installed. From what information is available it appears that a substantially standardised design has now been evolved and that manufacture has been planned for large-scale production.

The most important differences between this system and the Unit Bay 1B system are believed to be:—

(*a*) The 0.265 in. diameter tubes, though references have recently been made to tubes of 0.370 in. diameter for new work.

(*b*) The mounting of the repeater equipment on poles or walls.

(*c*) The switching of spare tubes and repeaters if a fault develops in the working circuit.

(*d*) The automatic equalisation for temperature variations at each repeater station by means of a filter-amplifier-detector-thermistor unit operating on the feedback network of each repeater.

In 1944, the A.T. & T. Company announced a 5-year coaxial cable programme involving 7,000 route miles of construction, which is now going forward at a rapid pace.

5. PRINCIPLES OF REPEATER EQUIPMENT DESIGN.

5.1. General.

It is proposed in this section (*a*) to consider what fundamental factors govern the design of wideband systems, (*b*) to discuss how the design depends on the various component parts and functions of a system, and (*c*) to indicate some of the possible lines of future development. It will be assumed throughout that the transmitted wave is amplitude modulated in accordance with established practice on wire circuits. There are, however, other methods capable of transmitting intelligence over coaxial tubes, *e.g.*, frequency modulation, but they have not yet been employed commercially by the British Post Office and it is not proposed here to speculate on their possibilities.

An ideal transmission link can be defined as one in which the received signal is an exact and instantaneous replica of the transmitted signal, provided that the transmitted signal is composed only of frequencies lying within the working frequency band of the system. In practice three main factors operate to a greater or lesser extent to prevent this being realised. These factors are the overall gain/frequency response, the phase/frequency response and the noise introduced into the system. The first two factors do not affect, at least in theory, the initial fundamental design since, provided the system is stable, they can be improved to any desired degree by inserting suitable correcting networks even after the system is installed. Noise, however, imposes definite limitations and it is on this factor that the whole economic design of a transmission system is based.

5.2. Noise.

It is in general not difficult to ensure that the noise picked up by the circuit from sources extraneous to the system is less than that generated in the H.F. circuit. This is rendered possible by the excellent shielding which is provided at high frequencies by the outer conductor of the coaxial tube and the screening of the repeater equipment. It can normally be presumed that noise generated in the H.F. circuit is produced at two points in each repeater section, *i.e.*, in the input and output stages of each repeater on the route. These two noises are quite different in behaviour and they must be considered separately.

5.2.1. *Resistance Noise.*

As is well known an E.M.F. due to thermal agitation exists across the terminals of any resistance so that in Fig. 11 a noise E.M.F. V_C is produced on the grid of the input valve of an amplifier due to the resistive component R_C of the impedance looking back into the cable through the input transformer. Valves also produce a similar type of noise due to current fluctuation in the cathode-anode path, and it is usually convenient to consider this noise as caused by a

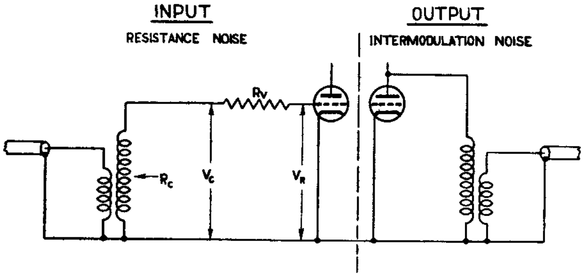


Fig. 11.—Sources of Noise in an Amplifier.

resistance R_V in the grid circuit. The total input noise E.M.F. at the grid of the valve is therefore V_R and is the thermal agitation E.M.F. produced by $R_C + R_V$. Noise generated in this manner in the input circuit of amplifiers will be referred to as resistance noise. The signal voltage at this point must obviously be very much greater than V_R.

5.2.2. *Intermodulation Noise.*

An amplifier is not a perfectly linear device even when the characteristics are improved by negative feedback, *i.e.*, the level of the output signal is not rigidly proportional to the level of the input signal. This non-linearity usually occurs in the output valve where the signal level is highest. It is well known that in such cases the passage of a signal produces spurious E.M.F's. The frequencies of these E.M.F's are sum and difference resultants of the constituent frequencies in the input wave. The number of such products generated by a complex wave is not generally appreciated ; for example, if the input wave is composed of 100 frequencies the number of third-order products ($f_1 \pm f_2 \pm f_3$) is about a million and in a working coaxial multi-channel speech system an astronomical figure is obtained. In such a system therefore this so-called inter-modulation noise will approach closely in " texture " to resistance noise with its myriad of discrete E.M.F's. Only in this respect, however, are the two types of noise similar. Resistance noise is produced continuously and it is quite independent of the presence of a signal. Intermodulation noise, on the other hand, is produced by the signal and its magnitude depends on the signal level, type of valve, output load, feedback, etc. A further difference is seen when it becomes necessary to determine the total noise produced by a chain of amplifiers. With resistance noise the total noise power is directly proportional to the number of amplifiers whereas for intermodulation noise the power may increase as the square of the number of amplifiers depending on the type of intermodulation term and the phase characteristics of the repeater sections. The determination of intermodulation noise was, until recently, very involved but a simpler treatment(53) is now available.

5.2.3. *Effect of Noise.*

The effect of noise in determining the operating levels and the result of these levels on the design of the system can best be demonstrated by an example. Consider a zero circuit composed of a chain of equally spaced amplifiers as shown in Fig. **12** (*a*), in which each amplifier compensates for the loss in the previous cable section, and assume that the total resistance noise at the zero level output of the chain is 20 db. greater than can be permitted. Fig. **12** (*b*) shows how the noise can be reduced by inserting a 20 db. pad at the output and restoring a zero circuit by adding a 20 db. amplifier at the transmitting terminal. The important point to note is that the output level from each repeater is now + 20 db. and not zero. If in Fig. **12** (*a*) the output stage of each repeater were just adequate to handle the power and to give a satisfactory value of the intermodulation noise power at the receiving terminal then in order to meet the power requirement of Fig. **12** (*b*), the output valve would have to handle 100 times the power, *e.g.*, an increase from a 5-watt valve to a ½ kW valve, and the linearity of the amplifier would have to be greatly improved. As a further example, if the resistance noise for the route shown in Fig. **12** (*c*) had been found to be 20 db. below the specified maximum limit then by increasing the noise to this limit the repeater output level could be reduced to −20 db. by inserting an additional amplifier and pad as shown in Fig. **12** (*d*). In theory a valve of 50 mW in the output stage would then suffice, but this is as impracticably small as the ½ kW valve was impracticably large. It will be shown later that the power range of valves suitable for wideband amplification is comparatively restricted.

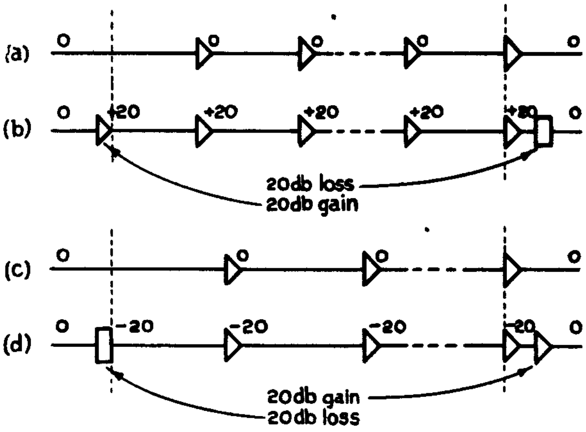


Fig. 12.—Effect of Varying Repeater Levels.

5.2.4. *Noise Limits.*

Recommendations for noise limits on trunk circuits have been made by the C.C.I.F. British practice within the framework of these recommendations is at present to allow 1 mV (psophometric) across a 600 ohm load at a zero level point on any individual trunk circuit and coaxial systems have been designed so that this figure is obtained on a 500 mile route composed of four 125 mile links. In 12-channel and lower frequency systems the component of the total noise due to intermodulation is of lesser importance than in coaxial systems where an accurate determination of this noise is essential for economic reasons. Intermodulation noise varies with the system loading and it has been assumed by Post Office engineers for design purposes that during the busy hour the average intermodulation noise power shall be equal to the resistance noise power. Under light loading conditions therefore the total noise voltage may decrease by nearly 3 db. In practice appreciable fluctuations will occur in intermodulation noise due, for instance, to the fact that it varies considerably with the system loading and with valve ageing. No direct allowance has been made for the noise contributed by the translating equipments required in a 500-mile circuit as this is normally small, *e.g.*, if the average noise voltage for each equipment is 0.12 mV the total noise on the system will only be worsened by 1 db.

5.3. Primary Design Parameters.

5.3.1. *The Design Parameters.*

The most important primary variables which occur in the design of a coaxial system are the frequency band, the repeater spacing and the size of the tubes. The width of the frequency band is usually fixed by traffic requirements and it is then apparently only a matter of deciding the optimum condition for frequency, repeater spacing and diameter of tube. Unfortunately, as will be shown, purely theoretical conclusions are complicated by various practical aspects which are not amenable to a unique mathematical treatment.

5.3.2. *Effect of Frequency Band.*

The designer is usually free to decide where the required bandwidth shall be allocated in the frequency spectrum, and it then becomes necessary to assess the relative advantages of operating at a high frequency where the ratio of maximum to minimum frequency is small or at lower frequencies with a larger ratio. The former may give simpler transformers and attenuation and phase equalisers, but the latter, within reason, offers a lower loss and a simpler repeater construction. For example, on the Unit Bay 1B system the provision of the lowest supergroup (60-300 kc/s) increases the frequency ratio from 10 to 50 and thereby complicates the repeater equipment out of proportion to the extra circuits provided. The addition of the frequency band required for an extra supergroup at the high frequency end of the band would be simple by comparison. It also appears that cases may arise in which considerable advantages accrue by shifting the band very much higher in the frequency spectrum, *e.g.*, from (1) to (2) in Fig. **13**.

The effect of changes in the bandwidth cannot be expressed in any simple general form. Consider, for example, a desired four-fold increase in the bandwidth ; the attenuation of a repeater section will be about doubled but this could be restored by doubling the diameter of the tubes or by halving the repeater spacing. The difficulty, however, then arises of designing a satisfactory repeater since the increase in bandwidth will mean: (*a*) a loss in gain per stage of 12 db. ; (*b*) a reduction in the overload point of 6 db. ; (*c*) an increase in intermodulation noise of at least 18 db., and (*d*) a reduction in realisable feedback of about 20 db. It is apparent, from these factors, that the degradation of the repeater with increasing bandwidth is spectacular. To some extent this can be mitigated by still further reducing the repeater spacing, but this introduces fresh difficulties associated with increased resistance noise, basic loss of equalisers, cable reflections, etc.

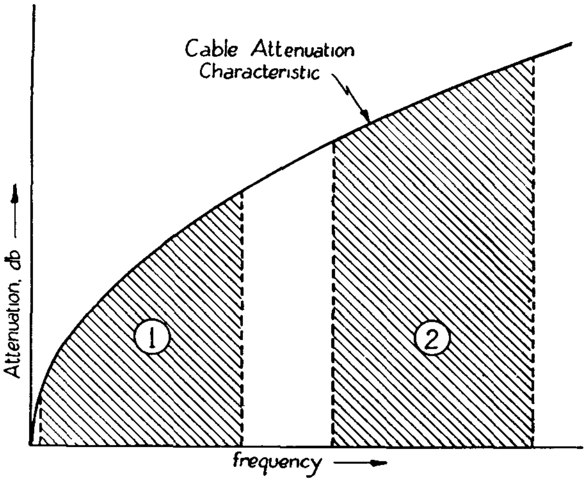


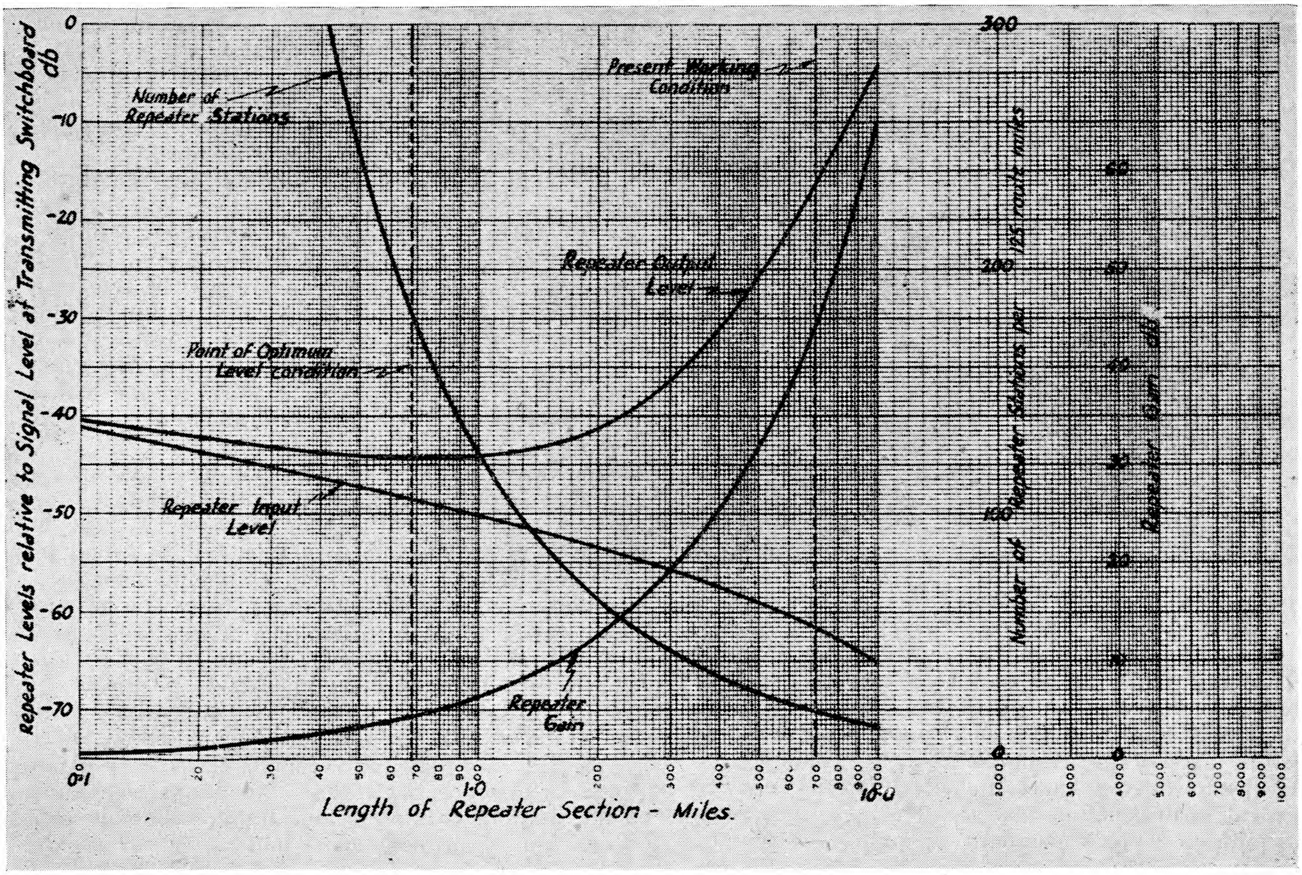
Fig. 13.—Location of Working Frequency Band on Wideband System.

5.3.3. *Effect of Repeater Spacing.*

Consider, as an example, a Unit Bay 1B route in which the 6-mile repeaters have a gain of 48 db. and an output level of −13 db. per channel. The input level to each repeater will therefore be −61 db. What then are the repeater requirements if the spacing be altered to 9 miles? Because of the fewer repeaters the resistance noise at the input to the last repeater will now be 6/9ths of the previous value, *i.e.*, 1.8 db. lower, so that the signal level at the input to each repeater can be reduced to −62.8 db. The new repeater gain will be 48 × 9/6 = 72 db. so that the output level becomes −62.8 + 72 = + 9.2 db. which is 22.2 db. higher than before (167 times the power). For the same margin against overloading the existing 3-watt valve would therefore have to be replaced by a (3 × 167) watt = ½ kW valve. Apart from the fact that no suitable valve exists in this class difficulties of power supply, ventilation and intermodulation render this 9-mile spacing inadmissible.

If a similar computation were made for a shorter spacing, *e.g.*, 4 miles, it would be found that a lower repeater gain together with a much lower power output would be required. The latter would, in fact, be so small that there is at present no valve sufficiently small which could take full advantage of this condition.

It can readily be shown theoretically that the minimum output power per repeater is obtained when the attenuation of each repeater section is 0.5 neper = 4.34 db., *i.e.*, about 0.6 mile with a ⅜ inch diameter tube and a bandwith of 3 Mc/s. Fig. **14** is a reproduction of a drawing made in March, 1936, showing the results of computations during the early design stages of the experimental London - Birmingham system. The optimum output level condition is at 0.68 mile, but it is not critical and little advantage would be gained by reducing the section length below 2 miles.



Relations existing between Repeater Spacing, Repeater Levels and Repeater Gain on the London-Birmingham Coaxial Cable. Assuming a Constant Resistance and Valve Noise Output at the Receiving Switchboard of 15.10^{-7} mW per 3000 c/s Channel Band. The Circuit has Zero Overall Transmission Loss.

FIG. **14**.—ORIGINAL DESIGN CALCULATIONS ON LONDON-BIRMINGHAM COAXIAL CABLE SYSTEM.

5.3.4. *Effect of Tube Diameter.*

Since the attenuation of a coaxial tube is almost inversely proportional to its diameter the general effect of tube diameter can be assessed as indicated above. To some extent an increase in cable diameter has the same effect as a decrease in repeater spacing, but the disadvantages of the latter are that the resistance noise, the attenuation of the route and terminal reflections are all increased. Practical limitations, however, become all-important and these are treated later.

5.4. Coaxial Cables.

A considerable amount of published data is available on coaxial cables and it is only possible to indicate here certain salient features. The combination of characteristics which makes a coaxial cable attractive compared with other types of conductors is low attenuation (attenuation $\propto \sqrt{\text{frequency}}/\text{diameter}$, when no dielectric loss is present), freedom from external H.F. interference (and therefore incapable of producing external interference), constant resistive characteristic impedance, velocity of transmission approaching that of light, simple construction and ease of repair. The most efficient tube, *i.e.*, minimum diameter for a given attenuation is obtained with copper (or pure silver) conductors having a ratio of inner diameter of outer conductor to inner conductor of about 3.6 with separators of minimum permittivity and zero loss. At high frequencies the current is constrained to a surface skin on each conductor of probably less than 0.001 inch and the rest of the conductor plays no useful part in reducing the attenuation. Actually a more satisfactory cable is possible with thin-walled conductors since a nearly constant attenuation is obtained and the phase characteristic is improved. The difficulty, however, with such conductors is to obtain a uniform, rigid and permanent construction. Since the centre conductor normally accounts for about 80% of the loss of a tube the application of this construction to the centre conductor only would result in a marked improvement and the thick-walled outer tube could remain to provide mechanical strength and shielding against external interference. No commercial cable has yet been constructed on these lines.

A somewhat remarkable fact about a coaxial cable is that the attenuation due to the dielectric is independent of the diameter of the tube. In large diameter tubes, therefore, where the conductor loss is low, serious attention must be given to the dielectric if its contribution to the total loss is to remain small. This is demonstrated in Fig. **15**.

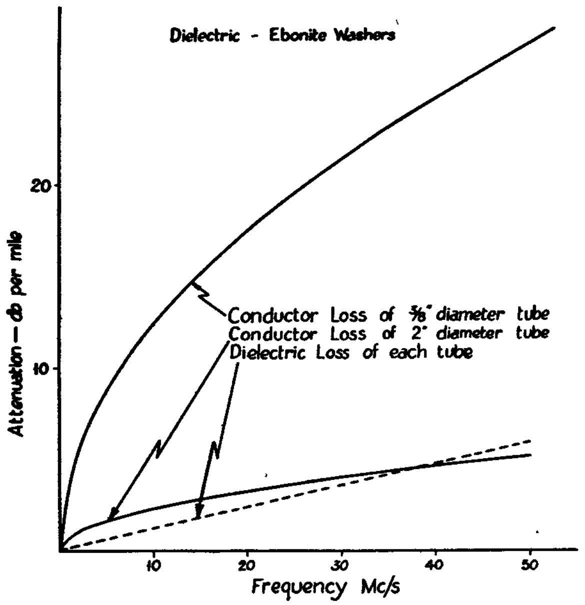


FIG. 15.—EFFECT OF DIELECTRIC LOSS IN COAXIAL TUBES.

Coaxial cables are at present being operated over only a comparatively narrow frequency band and there is no fundamental reason why advantage should not be taken of the favourable frequency characteristic to operate them at much higher frequencies, *e.g.*, to provide high definition television channels. For such a purpose a high standard of uniformity in the construction of the tubes will be required since irregularities set up a complicated system of internal reflections which can produce very uneven attenuation and phase responses. Irregularities may be due to variations in the dielectric or in the conductivity of the conductors, but the most usual cause is due to changes in the dimensions. Mismatching at the inputs and outputs of the repeaters may also cause trouble. Various authors have attempted theoretical treatments of the effects of irregularities, but more practical data is required for verification. A physical interpretation of the effect of irregularities may be obtained from the simple diagram shown in Fig. **16**. It is evident, for example, that there will be an increase in attenuation because part of the current has to travel a longer distance. Also, for the same reason, the double-reflected wave will arrive after the direct wave producing the " tail distortion " so well-known in television.

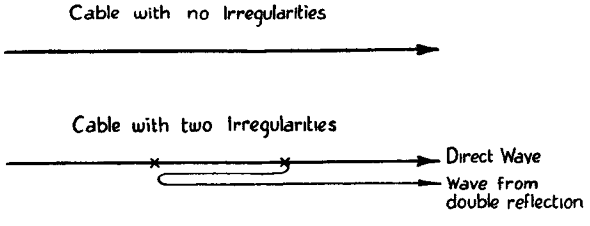


FIG. 16.—AN EFFECT OF CABLE IRREGULARITIES.

There are no theoretical reasons why loading should not be applied to a coaxial cable in order to produce a considerable improvement in its performance. The loading, however, would have to be virtually continuous and it has not hitherto been employed because of the difficulty of obtaining a satisfactory low-loss uniform magnetic material. Suitable methods might become available in the future which would then make possible a more economic design of cable.

Adequate permanence of the electrical characteristics of cables which have so far been laid does not in general appear to have been realised, and the ageing trend towards increased attenuation is attributed to the unstable construction of the outer conductor which consists of a layer of interlocking copper tapes. In an improved version which is now being installed the outer conductor consists of a single longitudinal tape bent round to form a tube with a butt joint and initial tests on this cable are very promising.

The largest cable tubes so far laid by the P.O. have a diameter of 0.45 inch, but it is possible that tubes having a diameter of one or more inches may be desirable if a satisfactory solution can be found for the very difficult problem of combining efficiency, uniformity and permanence in a cable which has also sufficient flexibility for drumming.

For multi-channel speech systems in this country the preferred arrangement appears to be the laying up of two tubes with the necessary supervisory pairs under one lead sheath, thus forming one self-contained cable system. Alternative methods using separate tubes or incorporating four or more tubes in the same cable require careful technical and economic consideration. Telephone pairs laid up in the coaxial cable are an essential requirement for the supervisory circuits on existing systems and it seems probable that the provision of these pairs will continue to be a necessity for future systems.

The early jointing of coaxial cables was unsatisfactory as was well demonstrated during the London blitz when joints at a considerable distance from a bomb crater were found to have become faulty. Improved technique resulting in stronger joints now appears to have solved the trouble and also to have reduced creepage faults to a negligible amount.

5.5. H.F. Amplifiers.

The variables in the design of an amplifier to meet a given performance are the valve parameters, number of stages, interstage couplings, transformers and feedback. All these factors are interdependent in complex relationships, but in the final design they must be so balanced that (*e.g.*, in the Unit Bay 1B repeater) (*a*) the correct gain is obtained, (*b*) the gain-frequency characteristic is flat, (*c*) the resistance and intermodulation noises are such that a predetermined overall noise value for the route is not exceeded, (*d*) there is an adequate overload margin and (*e*) none of the characteristics is appreciably degraded by power supply voltage variations, valve replacements, temperature changes, or by variation due to normal ageing in any of the valves or other components. Other requirements are that the valves must have a long life, the power required must be capable of being transmitted over the tubes and adequate ventilation must be assured without reducing the screening.

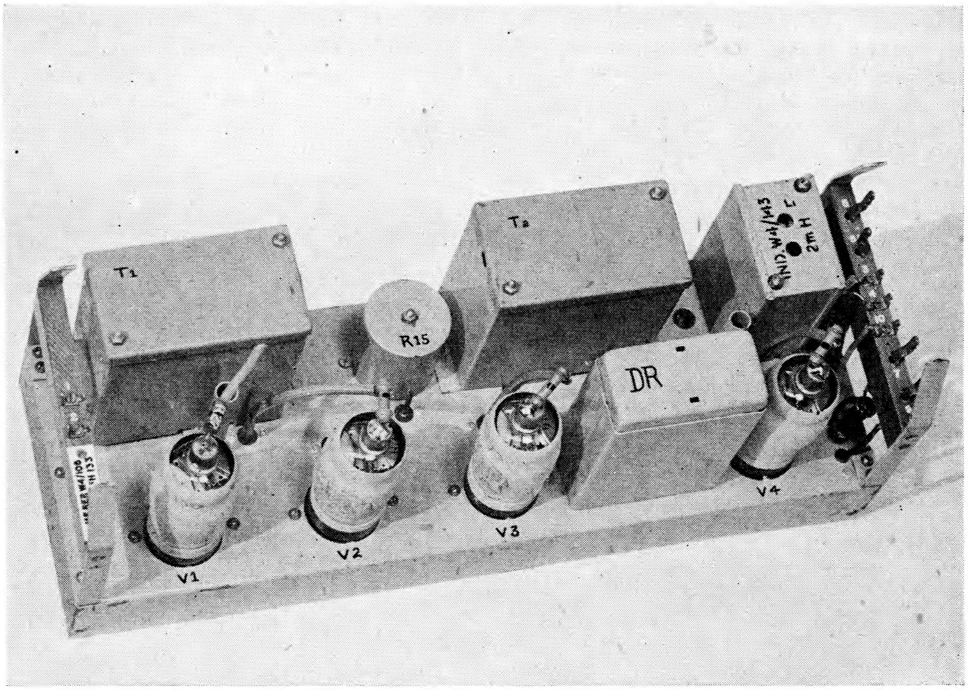


FIG. **17**.—UNIT BAY 1B. COAXIAL CABLE REPEATER AND PILOT SELECTOR.

The principle of negative feedback together with an understanding of the attenuation-phase relationship of minimum phase networks has revolutionised amplifier design, but, particularly at high frequencies, the design of a feedback amplifier is far from simple because of the complex networks set up by spurious inductances and capacitances. In the Unit Bay 1B repeater the attenuation-frequency response of the amplifier and feedback path has to follow a predetermined curve from about 3 kc/s to 60 Mc/s. Fig. **17** shows the standard 3-valve repeater which is the most important unit in the whole coaxial system. This repeater has a gain of 48 ± 0.1 db. over the frequency band 60-2852 kc/s, and Fig. **18** illustrates the extraordinary stability which is obtained by feedback. With very wide frequency bands, *e.g.*, over 10 Mc/s, the valve characteristics seriously limit the amount of feedback available, with the result that the general stability and performance of such an amplifier may decrease below tolerable limits.

The general technique and construction of the input and output transformer networks is now fairly well established, for example, on the Unit Bay 1B repeater the transformers have a ratio of maximum frequency to minimum frequency of 50 and a band of nearly 3 Mc/s and yet each is flat to about ± 0.05 db. Ferromagnetic intermodulation is just noticeable at low frequencies in the cores of these transformers, but it is unlikely to be observed on any new designs since it is probable that higher frequencies and lower frequency ratios will be employed.

The interstage coupling of wideband amplifiers has greatly increased in efficiency (and complexity) since the simple resistance coupling in general use only 15 years ago. The problem is to build up the interstage capacity to present the greatest possible constant impedance over a given frequency band. Although couplings can now be devised which seem to approach

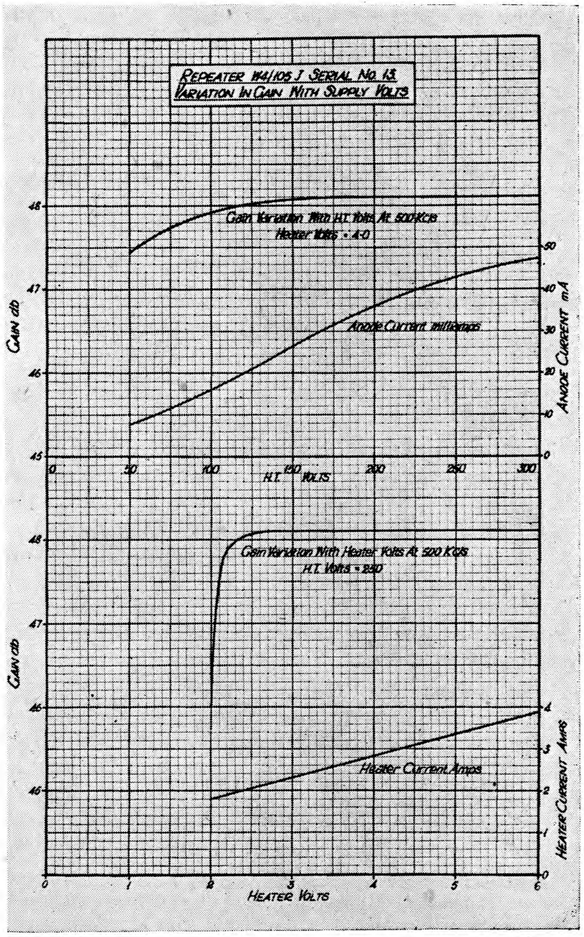


FIG. **18**.—COAXIAL REPEATER. VARIATION IN GAIN WITH SUPPLY VOLTS.

very closely to the theoretical limit the complexity is impracticable and a compromise is usually adopted which gives a reasonable efficiency. Fig. **19** is an example of the stage gains obtained with various couplings with a modern valve. The coupling characteristics are also governed by feedback-loop requirements, thus 4-terminal couplings are usually inadmissible because of the resultant 180° phase shift. There are also practical objections to complex couplings in that they become excessively sensitive to variations in valve capacitances such as might be obtained by valve replacement.

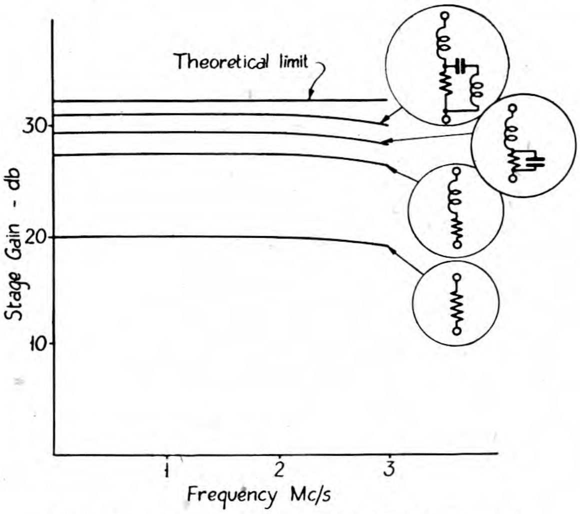


FIG. **19**.—TYPICAL STAGE-GAINS OBTAINED WITH VARIOUS COUPLINGS.

The design of amplifiers for television is, on the whole, similar to that for multi-channel telephony but with a somewhat different emphasis on the requirements, for example, the phase response is of particular importance not only in the amplifiers but throughout the whole system in order that the received waveform shall be a replica of the transmitted wave.

5.6. Valves.

The performance of the valves is undoubtedly the most important single factor which determines the capabilities of a coaxial system. The relevant valve characteristics are the figure of merit, the equivalent noise resistance, the input damping and the power handling capacity. The figure of merit which is the most important, is the ratio of the mutual conductance to the sum of the input and output working capacitances and it is a measure of the stage gain which can be obtained at any frequency. Given a very high figure of merit, a high stable amplifier gain can be obtained over a very wide frequency band and with a large amount of feedback. Unfortunately, the limiting value of the figure of merit for conventional pentodes appears to be nearly reached and it is probably necessary to look to a radical change in thermionic valve design if any material improvement is to be expected. Valve manufacturers have experimented with electron multipliers making use of secondary emission effects and beam deflection tubes, and although figures of merit of some twenty times that of a pentode have been obtained with the multiplier further development seems to be necessary to produce it in the reliable form which the amplifier designer is awaiting.

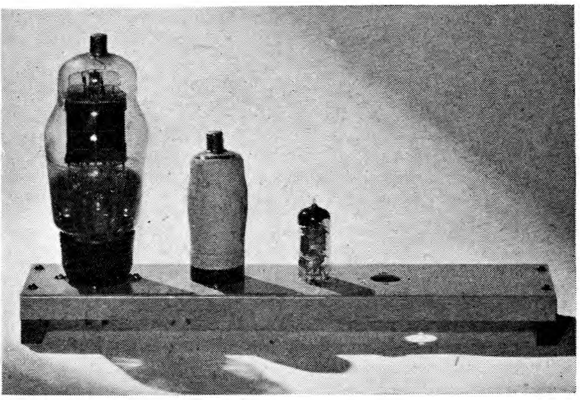


FIG. **20**.—H.F. AMPLIFYING VALVES.

Fig. **20** shows three stages in the development of valves (pentodes) for wideband working. It is evident that there have been improvements of a physical nature at least. It is not generally appreciated how inefficient and restricted the thermionic valve amplifier is, compared with an ideal amplifying device ; for example, a 3-valve wideband amplifier using the most efficient valves available requires about 10 watts to produce a substantially undistorted output of a few milliwatts, *i.e.*, an efficiency of about 0.1%. If the signal output required had been only a few microwatts the same valves would probably have been employed because the best figure of merit is only obtainable from valves with an anode current of about 10-60 mA. Since the efficiency in this case would be about 0.0001% it is apparent that the efficiency of existing amplifying devices falls far short of ideal amplifiers, particularly when linearity is a necessary requirement.

5.7. Repeater Equipment.

The permanent repeater equipment so far installed has been panel and rack mounted and an attempt has been made to conform so far as was practicable with existing lower-frequency practice. This has largely been achieved and as a result the transition up to a 3 Mc/s bandwidth has been readily accepted by regional staff. American practice on the other hand seems rather to consider these systems as an entirely new method of transmission and to design the repeater equipment purely on a performance basis with its own specially trained maintenance engineers. It seems very probable that in this country any considerable increase in frequency will dictate a more unorthodox design.

5.8. Supervisory Systems.

An adequate supervisory system is an essential part of any transmission scheme and this is particularly so for a coaxial system where the whole of the traffic depends on the continuity of a single path involving a large number of unattended repeater stations. The primary requirement of a supervisory system is that adequate information regarding the location and, if possible, probable nature of the fault shall be conveyed to the appropriate maintenance officer at the earliest moment. In the first coaxial system these requirements were considered to be best attained by arranging that, as far as possible, all fault indications should be received at one terminal station so that the engineer at that station would, when a fault occurred, be able to (*a*) locate and probably deduce the nature of the fault, (*b*) initiate repair directly with the maintenance engineer concerned, (*c*) advise traffic control of probable duration, (*d*) co-operate and offer advice during repair and give through-testing facilities and (*e*) check test and return to traffic at the earliest moment. This principle was found to work well and it was continued on the Unit Bay 1B system.

The design of the supervisory circuits requires as much care as the design of the H.F. equipment and it must be treated as an integral part of the complete system.

5.9. Power Supplies.

The general principle of providing A.C. power from public supply mains to a limited number of repeater stations on the system and feeding power from these stations over the coaxial tubes to dependent repeater stations has proved to be quite satisfactory, and it is likely to be retained in future designs. The safety measures now adopted for cable repairs appear to be adequate. It seems probable that the present spacing of about 30 miles between feeding points will still be obtainable on new system designs. The use of engine-alternator standby sets at power-feeding stations has greatly decreased the incidence of power faults, but there still appears to be a need for improved reliability in the power change-over equipment.

5.10. Repeater Stations.

Intermediate repeater stations in this country have so far without exception been housed in surface buildings such as the standard type shown in Fig. **21**. When suitable sites can be located there has been everything to recommend this method of construction and the cost of the repeater equipment, building and land is usually only a small fraction of the cost of the cable between repeater stations. The design is simplified because the equipment can be laid out in a form to give optimum performance and to be readily tested and repaired and, particularly in a new design, to give ample room to modify or extend as circumstances demand. Abnormal temperature and ventilating problems are not encountered in surface buildings. The installing and maintenance engineers can also work efficiently irrespective of climatic conditions and with adequate space for test equipment.

Various other methods of housing repeater equipment have been, and are still being examined with a view primarily to overcoming any difficulty which may be experienced in finding suitable sites if it is desired to locate repeater stations at spacings shorter than the existing 6-mile arrangement.

Possible alternatives are (*a*) to mount the equipment above ground in boxes on short poles or against walls (as is fairly common practice in the U.S.A.) or in kerbside pillars or cabinets or (*b*) underground in jointing manholes or specially designed chambers under the public highway. In all these proposals there are to a greater or lesser extent restrictions, *e.g.*, on the bulk of the equipment, the maximum power that can be utilised and the ease of installation and fault clearance ; but these do not necessarily preclude the future development of one or other of these alternatives for certain purposes. Since the cost of the repeater equipment is only a fraction of the cost of the cable it is probably uneconomical to restrict the frequency band by imposing undue limits on the repeater equipment. As the repeater spacing is one of the primary design parameters of a system the factors involved must be well studied in the design of any new type of transmission system.

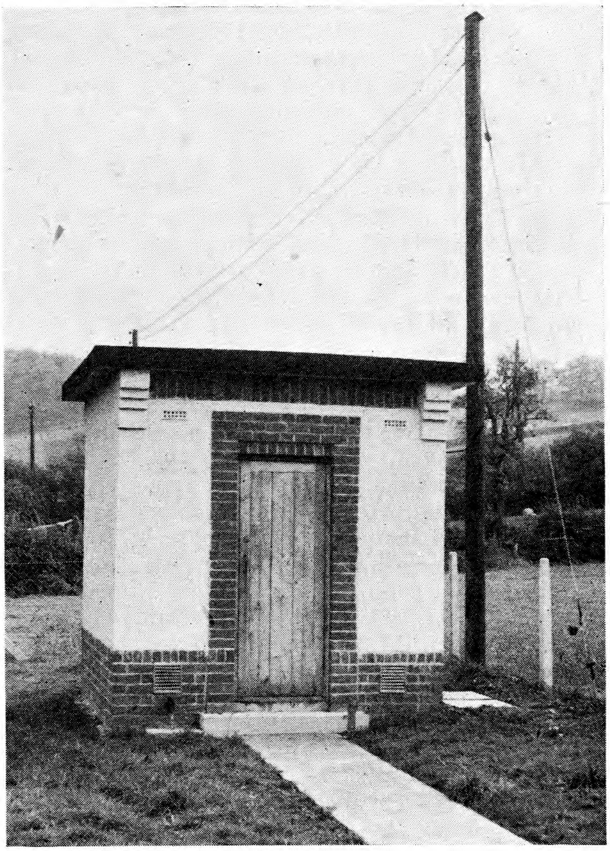


FIG. 21.—SMALL COAXIAL CABLE REPEATER STATION.

6. PRINCIPLES OF TERMINAL EQUIPMENT DESIGN.

6.1. General.

The standardisation of the triple modulation process and of all the frequencies concerned has greatly assisted in crystallising the design of the frequency translating equipment. The problems now reduce to the consideration of high performance filters, the generation of stable pure carriers and the long-term equipment stability. The levels of noise and unwanted intermodulation products need not provide limiting conditions since excessively high or low signal levels can largely be avoided at all stages in the translating equipment.

The aims of the designer of coaxial terminal equipment are:—

(*a*) To provide the best possible telephone channel performance and at least to meet prevailing international recommendations.

(*b*) To arrange that all circuits or blocks of channels are interchangeable at the predetermined traffic outlets.

(*c*) To ensure a high standard of inherent overall transmission stability and reliability.

(*d*) To arrange that all designs are suitable for bulk production and testing, are economical in space, and are easy to maintain.

The outstanding factors influencing each of these requirements are briefly as follows:—

6.2. Telephone Channel Performance.

Every telephone channel—that is, each side of every 4-wire circuit—must give a satisfactory performance in respect of (*a*) gain/audio frequency characteristic and (*b*) noise, which includes crosstalk, interference and thermal noise. The gain/frequency characteristic in a telephone channel is determined for practical purposes entirely by the terminal translating equipment. The noise is a spectrum of complex signals arising from both the line repeaters and the terminal translating equipment; the former source has already been considered in Section 5.2, and the latter will be discussed below.

6.2.1. *Frequency Characteristic.*

Each telephone channel must at present (1946) fall within the limits shown in Fig. **22** (*a*) to meet the C.C.I.F. (1938) recommendation for 4 kc/s channel spacing. These limits apply to a complete audio-to-audio trunk circuit within one country's administration. Each section comprising a part of this trunk circuit must therefore be built to fall within much closer limits in order to achieve those of Fig. **22** (*a*) on a national trunk. Fig. **22** (*b*) represents the tolerances imposed by the P.O. Engineering Department for application to such individual coaxial sections.

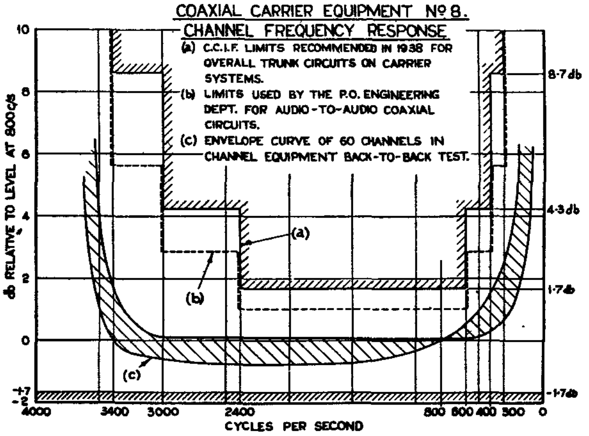


FIG. 22.—COAXIAL CARRIER EQUIPMENT NO. 8. CHANNEL FREQUENCY RESPONSE.

The envelope curves in Fig. **22** (*c*) show the response curves obtained in back-to-back tests on Channel Equipment No. 8. These can be taken as representative of average results on complete coaxial telephone channels on a Coaxial Equipment No. 8 because " within-channel " frequency variations arising from group and supergroup frequency translations should be almost negligible, *e.g.*, ± 0.1 db. are the limits set for such variations in one terminal of this equipment. The end channels of each group are most likely to approach the limit in this respect owing to the natural shape of the pass band in the band-pass filters. The repeatered line has a gain/frequency characteristic so nearly flat that no noticeable gain variations can result from this cause in any individual 4 kc/s channel.

Since modern trunk routing tends to use a group of twelve 4-wire circuits as its manipulative unit, group-to-group frequency characteristics measured between send and receive Group Distribution Frames are always recorded in coaxial acceptance testing. A gain/frequency " spread " of 2 db. is taken as the present Departmental acceptance limit which represents a generous figure for modern designs of equipment.

In the immediate future there is unlikely to be a demand for any substantial improvement in channel gain/frequency-response characteristic for coaxial trunk circuits, since these are already able to give a performance adequate for present telecommunication services. Development will rather swing towards achieving present standards with simpler and cheaper designs of channel translating equipment since channel bays at present account for three-quarters of the bulk and cost of a large coaxial terminal. In the design and production of the quartz crystal channel filters, improvement is desirable and likely. The metal rectifier ring modulator is satisfactory in principle for channel translation stages, but greater stability of characteristics with time will be sought in the future, to achieve a higher degree of channel carrier suppression.

6.2.2. *Noise.*

Noise, which includes all forms of unwanted signals, can be introduced into a telephone channel by the terminal equipment in a variety of ways, and it is necessary that the relevant factors involved shall be appreciated from the start of a design. In general, the possible sources of interference are:—

(*a*) Thermal noise.

(*b*) Impurity of carrier supply frequencies.

(*c*) Inadequate suppression of unwanted modulation products and, less likely, of carrier leaks.

(*d*) Stray coupling between signal paths.

(*e*) Intermodulation.

(*f*) Mains hum entering audio circuit paths.

6.2.2.1. *Thermal Noise.*

This should not be a limiting parameter in terminal translating equipment, as points of very low level can be avoided. The total thermal noise power arising from terminal translating equipment on a coaxial circuit is unlikely to give rise to an E.M.F. greater than 0.25 millivolt psophometric per channel.

6.2.2.2. *Impurity of Carrier Supply Frequencies.*

Any frequencies entering modulators at the carrier input terminals will tend to produce modulation sidebands. If the carrier possesses a superimposed leak from another frequency—due say, to imperfect suppression of adjacent harmonics of the carrier source by the carrier selecting filter—then the associated signal path may also appear as a low level sideband in the wrong channel as a result of modulation by the unwanted carrier source harmonic. This may appear as either intelligible or unintelligible crosstalk. A contaminated carrier may also introduce noise in the signal band. Channel crosstalk into circuits spaced three channels away in the frequency spectrum may arise by this means from impure group carriers, which are selected from harmonics of 12 kc/s ; *e.g.*, channel 4 in a group may receive crosstalk from channel 1 which is 12 kc/s away. This mechanism may also cause adjacent channel inverted crosstalk if the channel crystal filters do not provide adequate adjacent channel and upper sideband discrimination: It is now accepted as one condition for freedom from crosstalk that impurities on carrier supplies should be at least 70 db. below the wanted carrier level.

Even greater care must be exercised in ensuring that the input frequency to a harmonic generator is pure. For example, it has been found that, in the 124 kc/s supply (*i.e.*, 31st harmonic of 4 kc/s) feeding the supergroup harmonic generator, neighbouring harmonics 4 and 8 kc/s away must be suppressed by 90 db., relative to the wanted carrier, if crosstalk complications arising from the resulting supergroup carrier impurities are to be completely avoided.

6.2.2.3. *Inadequate Suppression of Unwanted Modulation Products and Carrier Leaks.*

Lower sidebands are selected at the output of each modulator and it is the function of the band-pass filters to suppress all unwanted products, particularly the upper sideband, the carrier and the original signal band. The upper sideband is relatively more difficult to suppress as the ratio of frequency gap between carrier and sideband to the carrier frequency gets smaller. It can be seen from Fig. **6** that in the channel translation stage the carrier frequencies are at the edge of the sideband and the necessary suppression of the upper sideband and carrier demands that crystal filters be used. The group and supergroup conditions are much easier and can be met by coil-condenser filters. In all three cases the suppression of the upper sideband relative to the lower should exceed 70 db. to ensure freedom from crosstalk difficulties. Typical filter curves for the Coaxial Translating Equipment No. 8 are shown in Fig. **23**.

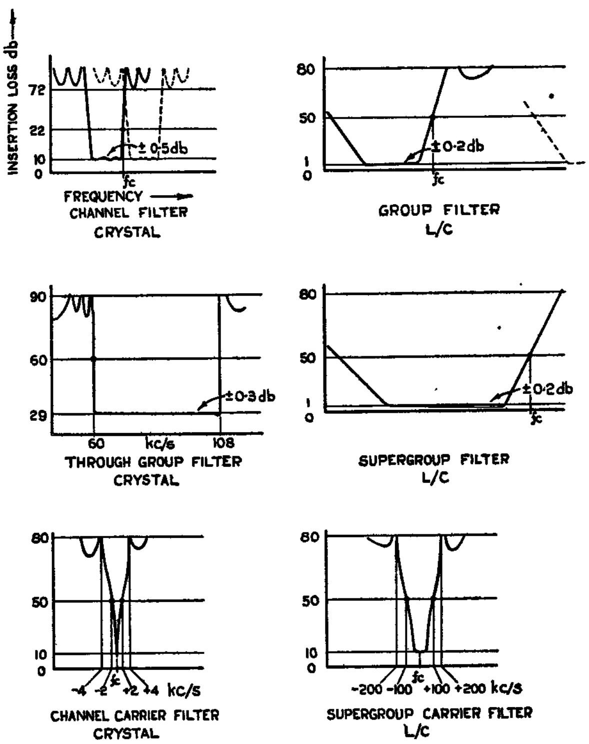


Fig. **23**.—Coaxial Carrier Equipment No. 8. Insertion Loss Characteristics of Various Filters.

Supergroups Nos. 1 and 3 require special consideration as already shown in Section 3.2.6.3, because it is necessary to eliminate any interference between the basic supergroup signals associated with these two supergroups and supergroup 2, which happens to occupy the same frequency band as the basic supergroup. A high degree of carrier suppression is not theoretically essential at a modulator output. It is desirable, however, for three important reasons (a) to reduce signal loading power on the repeatered line, (b) to reduce possibilities of intermodulation frequencies appearing, and (c) to simplify routine testing of the system by removing permanent voltages from signal paths so that direct measurement of test signals can be made easily. Balanced modulators can ideally give a high degree of carrier suppression relative to sideband output, but the balance is liable to be upset by differential ageing in the modulator elements. This undoubtedly occurs in metal rectifier and, to a less extent, in balanced valve modulators. Balance adjustments can be instituted in maintenance routines, but it is not good practice. The best method is to provide sufficient carrier suppression in the band-pass filters because these are stable, sealed passive networks. Any extra carrier suppression which the modulators may give is then a working safety factor. Ideally all carrier leaks should, therefore, be suppressed by the order of 50 db. below relative test level.

Carrier leak voltages alone are not likely to lead to continuous beat tones, such as whistles in telephone channels, since all carrier frequencies are multiples of 4 kc/s and any beat frequencies between them therefore fall between channel passbands. Audible tones might be produced on the London-Newcastle Tubes 1 and 2 system, however, because the lowest four supergroups employ different carrier frequencies from the higher ones, which use the C.C.I.F. system of Fig. **6**.

6.2.2.4. *Stray Coupling between Signal Paths.*

To avoid trouble from this source it is necessary to design all H.F. equipment to present, as far as possible, a perfect coaxial circuit. The mechanical principles of design must be subordinated to this aim, often at the expense of accessibility of components. Passive networks, *e.g.*, filters, can be made to behave more like coaxial structures than valve networks.

6.2.2.5. *Intermodulation.*

It is well known that unwanted products from balanced modulators can be reduced to a low order by operating them with low signal and high carrier levels. These products can be divided into two classes (a) those which can be suppressed by the attenuation regions of succeeding filters and (b) those which cannot be filtered out because they fall into a transmission band. Class (a) offer no great difficulties. Class (b) can set a limit on the permissible signal levels at which a modulator can be operated. For example, if continuous 2 kc/s signals are sent on channels No. 11 in group 2 and No. 11 in group 1 both in supergroup 3, they will appear at the output of the supergroup 3 modulator at frequencies of 750 kc/s and 798 kc/s. One possible 3rd order intermodulation term produced in this modulator would be (2 × 750) – 798 kc/s, *i.e.*, 702 kc/s, which would ultimately appear as a 2 kc/s whistle in channel No. 11 on group 3 in the same supergroup. The supergroup modulator design must ensure that such whistles occur at a sufficiently low level to be negligible.

6.2.2.6. *Mains Hum.*

Two types of mains interference may occur in the audio outputs, namely modulation hum and direct mains frequency pick-up. In carrier equipment the former is easily eliminated as it can only enter on carrier frequencies as a 50 c/s modulation. Adequate decoupling of power supplies removes such sources. Direct pick-up of mains hum may occur in channel receive amplifiers or audio terminating transformers. These sources must be screened from mains power wiring by careful design.

6.3. Circuit Flexibility.

Blocks of channels can only be regarded as interchangeable if the frequency-transmission characteristics of all similar sections of the equipment fall within the same carefully specified limits. It is therefore not desirable to use adjustable networks on, say, demodulation stages to correct performance irregularities on modulation equipment. The overall permissible margin of performance must be apportioned during the design between the various sections of the equipment and these limits should then be rigidly maintained in all production.

As shown in Fig. **22** (*a*) the maximum permissible frequency response range of any channel between 600 and 2400 c/s over a complete trunk circuit may be taken as ± 1.7 db. ; this circuit may comprise as many as 8 supergroup and 8 group frequency translation stages as well as two channel frequency translations, so that a very close tolerance must be set on the performance of the individual band-pass networks and amplifiers. This aspect has been discussed in Section 6.2.1.

6.3.1. *Through-Group Working.*

It has already been shown that one advantage of a coaxial trunk system is that circuit routing can use as its unit the 12-channel group in the basic group band 60-108 kc/s. Such groups can then be directly connected via Group Distribution Frames to 12 channel spurs, or interconnected between different supergroups, provided that there are no interfering signals present on the group output terminals. On groups derived from coaxial systems, this condition can be ensured only by introducing steep-sided group band-pass filters in the Group Distribution Frame. These remove all vestiges of adjacent group signals so that they cannot appear as crosstalk later in the trunk network. The exact degree of adjacent-group attenuation necessary in these through-group filters depends on the types of carrier systems being interconnected (40a), and in some cases, *e.g.*, coaxial-to-coaxial connections where a complete supergroup is passing through with its five groups in unchanged order, it is theoretically possible to dispense with these extra filters. On the other hand, the worst case, where some groups are being extracted and the remainder rearranged, may demand as much as 70 db. attenuation to the adjacent group on each side to avoid crosstalk. The Through-Group Filter is therefore designed to cover this condition. The type intended for use with the Coaxial Equipment No. 8 is hermetically sealed and employs eight quartz-crystal resonators with soldered-on wire connections. It has a passband flat to within ± ¼ db. over the 12 channels in the range 60-108 kc/s with over 70 db. discrimination to adjacent groups. The basic passband loss is built out by attenuators to a total of 29 db. which is the level difference standardised between the input and output of the Group Distribution Frames. Fig. **23** shows the insertion loss characteristic of this filter.

6.3.2. *Through-Supergroup Working.*

When the coaxial trunk network is fully developed it is probable that traffic routing in blocks of 60 circuits will have advantages worth consideration. For this purpose a through-supergroup filter with a flat passband in the range 312-552 kc/s will be used and such a filter is in course of development. No doubt, in the more distant future supergroups will be extracted at their line transmission frequencies. Such a scheme is already under consideration in America, but has not yet received attention in this country.

6.4. Circuit Stability.

It is now apparent that without some form of overall gain control a long-term stability within ± 1 db. for an audio circuit carried over several coaxial systems is unlikely to be realised, as normal ageing and temperature effects in components alone can cause this figure to be exceeded. The effect of power supply variations is also by no means negligible and it appears that voltage-regulated A.C. operated coaxial equipment is preferable to existing battery driven equipment in this respect.

Supergroup automatic gain control between terminals (Section 3.2.6.4) was therefore chosen as the most economic method of achieving circuit stability and with this feature on the Carrier Equipment No. 8 stability limits of ± ¼ db. should be obtained for each supergroup path. An overall long-term stability within ± 1 db. should thus be attained on the audio channels, irrespective of small variations in the repeatered line and in the unstabilized group and channel stages. Suitable recording equipment has been designed to assist in correlating H.F. and L.F. levels, power supply variations and atmospheric conditions.

This automatic gain control principle could readily be extended to operate between basic group frequencies for small blocks of circuits or for extension over 12-channel routes. It is also possible to operate such a control between basic supergroup and basic group frequencies if special conditions make this more convenient.

7. RELIABILITY OF COAXIAL CABLE SYSTEMS.

7.1. Transmission Line.

It is almost impossible to over-emphasize the importance of reliability in wideband systems. This word pursues (or should pursue) the designer from the moment he commences planning the system and the fault-returns after the system is in service are a measure of his success. A brilliant initial performance obtained by too critical or complex circuits at the expense of a subsequent high fault liability and continuous maintenance is likely to be inferior to a more simple reliable system. Reliability is not obtained as the result of attention to any one detail, as, for example, the testing of components or the training of maintenance staff, the soldering of joints or rigorous inspection, but is only achieved by painstaking, non-spectacular progress in improving all the influencing factors. The analysis of system fault-returns is invaluable in determining the weakest links and in formulating a well-balanced economic treatment for improving the system performance. The factors chiefly concerned in influencing the fault records are:—

(*a*) *Design.* This includes not only the choice of circuits but the actual selection of the components, factors of safety, layout of the equipment, testing facilities, ventilation, etc.

(*b*) *Manufacture.* Careless construction may provoke incipient faults which even the best inspection may fail to detect. Cleanliness, mechanical rigidity and correct soldering are all important.

(*c*) *Inspection.* Meticulous inspection at all stages is essential on a much more intensive basis than is usually adopted, *e.g.* individual-inspection of every soldered joint in the H.F. equipment and shock testing. Any slackening of inspection will later become only too evident in the fault returns of the system.

(*d*) *Routine Maintenance.* This has been studied with great care over a number of years and as a result it has been decided to reduce it to a bare minimum. On reliable equipment it appears that more faults are produced or weaknesses caused by excessive maintenance than if the equipment were left well alone. At intermediate repeater stations on the Unit Bay 1B system maintenance is called for only at yearly intervals and even then it is comparatively restricted.

(*e*) *Fault Repair.* Faults can be divided into two classes—(*a*) those which cause a degradation in the system performance which, however, is insufficient to warrant withdrawing it from service and (*b*) those which definitely interrupt traffic. The latter class can be further subdivided into faults which the control terminal can rapidly correct to enable the system to be returned to traffic and faults which can only be repaired by personal attendance at the station. These last faults are particularly serious and a traffic break of 1 hour or more must be envisaged if a replacement item has to be obtained. It has been found, however, that the reliability of the equipment can be improved to the state when such occurrences are comparatively rare.

As an example of the type and duration of faults which are now occurring on coaxial systems the table below (extracted from the latest fault records available) shows the total faults which caused a loss of traffic on the four Unit Bay 1B (modified) transmission links which were in operation during the first 10 months of 1945. In assessing these faults it must be remembered that these systems were installed under urgent war conditions with a lower standard of inspection than is now enforced and that the maintenance staff had received only a minimum of training. These figures (approx. 7 hours per system per year) are very much better than those obtained on the original coaxial systems and it is confidently expected that a further improvement will be realised on future systems. A point of interest is that the fault record of a system improves continuously from its in-service date.

TABLE 2.

TOTAL TRAFFIC INTERRUPTION TIME DUE TO ALL FAULTS ON UNIT BAY 1B (MOD.) TRANSMISSION LINKS.

Systems reviewed	Inverness-Wick Bristol-Exeter	Selly Oak-Old Boston Colwyn Bay-Holyhead
Period under review	10 months	January to October 1945 inclusive
Total System Mileage	336	

Number of repeater stations including terminals 33

	Unit Bay 1B equipment	Power Supply	Cable
Total duration of Faults	13 hrs 26 mins.	7 hrs. 6 mins.	5 hrs. 5 mins.
Number of Faults	12	27	3
Longest Faults	3 hrs. 27 mins. (slack transformer nut) 2 hrs. 10 mins. (power condenser)	2 hrs. 5 mins. (faulty stand-by) 0 hrs. 50 mins. (faulty standby)	3 hrs. 15 mins. 1 hr. 35 mins. (both low I.R. on pairs).
Shortest Fault	10 mins. (noisy repeater)	½ min.	15 mins.

7.2. Terminal Equipment.

The general principles laid down for the repeater equipment apply equally to the terminals. The master oscillator in the carrier generating equipment is the most important individual unit as it is the origin of all the carrier frequencies. Automatic change-over to standby is therefore provided to prevent any loss of circuits if this master should fail.

In the Coaxial Equipment No. 8 the general plan has been to provide rack-mounted spare standby units for all types of filters, modulators and amplifiers, but manual change-over by H.F. test leads has replaced automatic change-over devices. This greatly simplifies the equipment and does not detract from its reliability, as suitable automatic switching systems would be both complicated and bulky.

Crystal filters using gold-plated resonators have proved extremely reliable, but poor quality condensers, a batch of which was unavoidably used in a war-time contract, have given considerable trouble.

There is every reason to hope that a high degree of reliability will be obtained from the Coaxial Equipment No. 8 as a result of the experience on the earlier experimental installations.

8. ECONOMICS.

Although it is not possible to enter here into a full economic study of various types of transmission it is desirable to include some notes on an economic comparison between coaxial, 12 and 24-channel carrier, and audio systems. As the result of a recent comprehensive economic study the following very general conclusions emerge:—

(*a*) Audio or coaxial transmission provides the most economic system under any condition. 12-channel is not a successful competitor and 24-channel carrier is only advantageous as a conversion scheme for existing 12-channel carrier systems.

(*b*) For circuit requirements of 600, 200 and 150 circuits, coaxial is cheaper than audio if the circuit lengths are in excess of about 30, 50 and 120 miles respectively.

An important factor in favour of coaxial is the facility with which additional circuits can be rapidly provided up to the present limit of 600 per pair of tubes by a simple extension of the terminal equipment.

9. CONCLUSION.

Coaxial cable transmission is now considered to be firmly established as a means for providing a reliable and economic trunk network in this country. In view of its rapid rise in eleven years from an unknown to a standard system forming a considerable proportion of the country's trunk network some hesitation must naturally be felt in predicting future developments. There is, however, as far as can be seen at present, no reason to suppose that this type of transmission will be rivalled, much less out-dated, in the cable field during the next decade. Competition from any new type of transmission will have to reach a high standard because coaxial technique itself is only in its early stages and foreseeable developments are likely to improve greatly the performance of coaxial cable systems in the future. It is considered therefore that multi-channel telephony can be safely planned on the basis of coaxial cable transmission. If, as appears probable, a television network will be required in this country it will be forced to employ either radio or cable links. Where cable transmission is chosen, coaxial working would undoubtedly be employed.

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